VOLUME IV
FLIGHT TEST MANAGEMENT

CHAPTER 5

FLIGHT TEST INSTRUMENTATION

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14.1 INTRODUCTION TO DESIGN

14.1.1 INTRODUCTION

The purpose of any test is to collect data which are then used to evaluate the article being tested. Instrumentation is the term applied to the equipment used to collect these data.

Flight test programs invariably represent a significant investment of resources, and therefore considerable care must be devoted to identifying the specific requirements for the flight test and to assure that the data systems will yield the required information. The first step towards the flight test instrumentation system then is a clear statement of the objectives of the flight test programs. These objectives are drawn up by those who require the information for analysis. On the basis of these objectives, the flight test organization will prepare a preliminary flight test program, a list of parameters which must be measured, and other special requirements.

The instrumentation design phase begins when the test engineers develop a measurements list. Using this list, the instrumentation engineer produces an overall design approach for the instrumentation system required to obtain the data measurements.

In the instrumentation development phase, the hardware and software of the instrumentation system are developed by technical specialists. In this phase, commercially available parts are chosen and ordered, and parts for the system which must be made in-house are designed and fabricated. At the end of this phase, the actual hardware and software will have been obtained, calibrated, and installed.

When the total instrumentation system, or at least major parts of it, is ready, it then passes into the test phase. The importance of this phase is often underestimated, with the result that startup problems sometimes cause delays in the transition to the operational phase of the flight test program. It is very important to take instrumentation testing requirements into account when planning a flight test program, for in some cases testing has required as much time as the design and development phases together. Many of the tests can be performed in the laboratory, but experience has shown that actual flight testing of the equipment is essential. The test is used to train equipment operators and maintenance personnel and to develop maintenance schedules.

14.1.2 FACTORS INFLUENCING INSTRUMENTATION SYSTEM DESIGN

From an instrumentation point of view, some of the possible approaches to the test program may require much more complicated instrumentation systems than others. For this reason flight test objectives must be specific and detailed and a discussion about them must be held at an early stage for justification of the reasons behind their selection. The test objectives dictate both the data to be acquired and the success criteria imposed on those data.

The measurements list:

Definition. A measurements list is a catalog of all the quantities to be measured in a test program. Typically, a measurements list contains as a minimum: the measurement name, range of values expected, accuracy, resolution, frequency response, location on the aircraft, environmental conditions, phase correlation with other measurements, flight importance, measurement priority, and remarks. This measurement list is prepared by the test engineer. The instrumentation engineer should become involved at an early stage and may contribute instrumentation-oriented requirements to the list. Figure 1 is an example of a measurements list. The exact form of the list may contain more or less information depending on the complexity of the system. The measurements list is a good indicator of system cost, schedules amount of data processing required, etc. A measurements list, being the link between the flight test engineer and the instrumentation engineer, should be kept up-to-date and reflect all coordinated changes.

Review of the measurements list. Just why is a measurements list so vital to the instrumentation engineer? It contains the essential information he needs to begin the system design work. The design approach can be determined only after considering these requirements. The test engineer should provide a measurements list as early as possible in the program. It can be very helpful if complete; if incomplete, it can initiate only a partial -- and sometimes false -- start.

The instrumentation engineer assumes the responsibility for challenging the requirements imposed by the measurements list. This validation process is a constructive practice in which the test engineer must participate. Such discussions have led to solutions which did not require costly special equipment. The instrumentation engineer, in arguing for his position, acts to prevent excesses and special cases from being imposed through default. It must be

	MEASUREMENT TYPE	LOCATION	RANGE	RESOLUTION PERCENT FULL-SCALE	ACCURACY PERCENT FULL-SCALE	FREQUENCY RESPONSE HERTZ	PRIORITY[1]
1	AIRSPEED	AFT EQUIP BAY	0-500 kts	0.1	+/-1	1 HZ	P
2	ALTITUDE	AFT EQQUIP BAY	0-40,000 ft	0.1	+/-1	1 HZ	P
3	ANGLE-of-ATTACK	NOSE BOOM	+35°,-15°	0.1	+/-1	3 HZ	P
4	ANGLE-of-SIDESLIP	NOSE BOOM	+1-25°	0.1	+/-1	3 HZ	P
5	PITCH ALTITUDE [2]	AFT EQUIP BAY	+1-85°	0.1	+/-1	3 HZ	P
6	ROLL ALTITUDE [2]	AFT EQUIP BAY	+1-180°	0.1	+/-1	3 HZ	P
7	YAW ALTITUDE [2]	AFT EQUIP BAY	+1-180°	0.1	+/-2	3 HZ	P
8	PITCH RATE	AFT EQUIP BAY	+1-100°/sec	0.1	+/-1	20 HZ	P
9	ROLL RATE	AFT EQUIP BAY	+1-250°/sec	0.1	+/-1	20 HZ	P
10	YAW RATE	AFT EQUIP BAY	+1-100°/sec	0.1	+/-1	20 HZ	P
11	NORMAL ACCELERO-METER	C.G.	+8g, -2g	0.1	+/-1	10 HZ	P
12	LONG ACCELEROMETER	C.G.	+2g	0.1	+/-1	10 HZ	P
13	LAT ACCELEROMETER	C.G.	+2g	0.1	+/-1	10 HZ	P
14	FUEL FLOW	AFT EQUIP BAY	(COUNTER)	0.3	+/-0.3	———	P
15	ALTITUDE RATE [3]	AFT EQUIP BAY	+1-30,000 ft/min	0.1	+/-2	1 HZ	S
16	ENGINE INLET TEMP	ENGINE INLET	0-250 °F	0.1	+/-2	3 HZ	S
17	AILERON POSITION	LEFT WING	+1°-125°	0.1	+/-1	3 HZ	P
18	STABILIZER POSITION [4]	AFT EQUIP BAY	+10°,-11°	0.1	+/-1	3 HZ	P
19	RUDDER POSITION [4]	AFT EQUIP BAY	+1° - 15°	0.1	+/-1	3 HZ	P
20	NOZZLE POSITION	ENGINE	0-95°	0.1	+/-1	3 HZ	P
21	ENGINE RPM	AFT EQUIP BAY	0-100%	0.1	+/-1	1 HZ	P
22	EXHAUST GAS TEMP [5]	ENGINE TAIL PIPE	+500°C- +700°C	0.1	+/-2	3 HZ	P
23	EVENTS	AFT EQUIP BAY	(COUNTER)	——	——	——	S
24	TIME	AFT EQUIP BAY	8 HOURS	1 MSEC	——	——	P

[1] P = PRIMARY; S = SECONDARY

[2] DERIVED from SYNCHRO OUTPUTS of SHIP'S GYROS

[3] DIFFERENTIATION of ALTITUDE

[4] OPT'S on CONTROL CABLES

[5] DETERMINES ENGINE LIFE

FIGURE 1. TYPICAL MEASUREMENTS LIST

understood, however, that the instrumentation engineer does not have the last word about the measurements list. The test engineer can insist and, though sometimes at a very high cost, get every measurement he needs.

The instrumentation engineer will usually attempt to negotiate an adjustment of parameters on the measurements list (such as measuring range, accuracy, frequency response) so as to better match those of more commonly supplied or stocked parts. Adjusting parameters on the measurement list can reflect savings in both cost and time by allowing the use of units already on hand and calibrated.

Development of the instrumentation system. Flight test instrumentation can be divided into two parts: the data collection subsystem and the data processing subsystem (Figure 2).

The data collection subsystem. This subsystem includes all measuring channels and their associated equipment which must be designed to function in the environmental conditions in the aircraft. This subsystem usually terminates with a recorder in which the information is temporarily stored. Some of the equipment used on the ground is often also regarded as part of this subsystem - for instance, the receiver and the ground recorder of a telemetry system, and even the measuring channels of any ground-based measuring equipment, such as cinetheodolites.

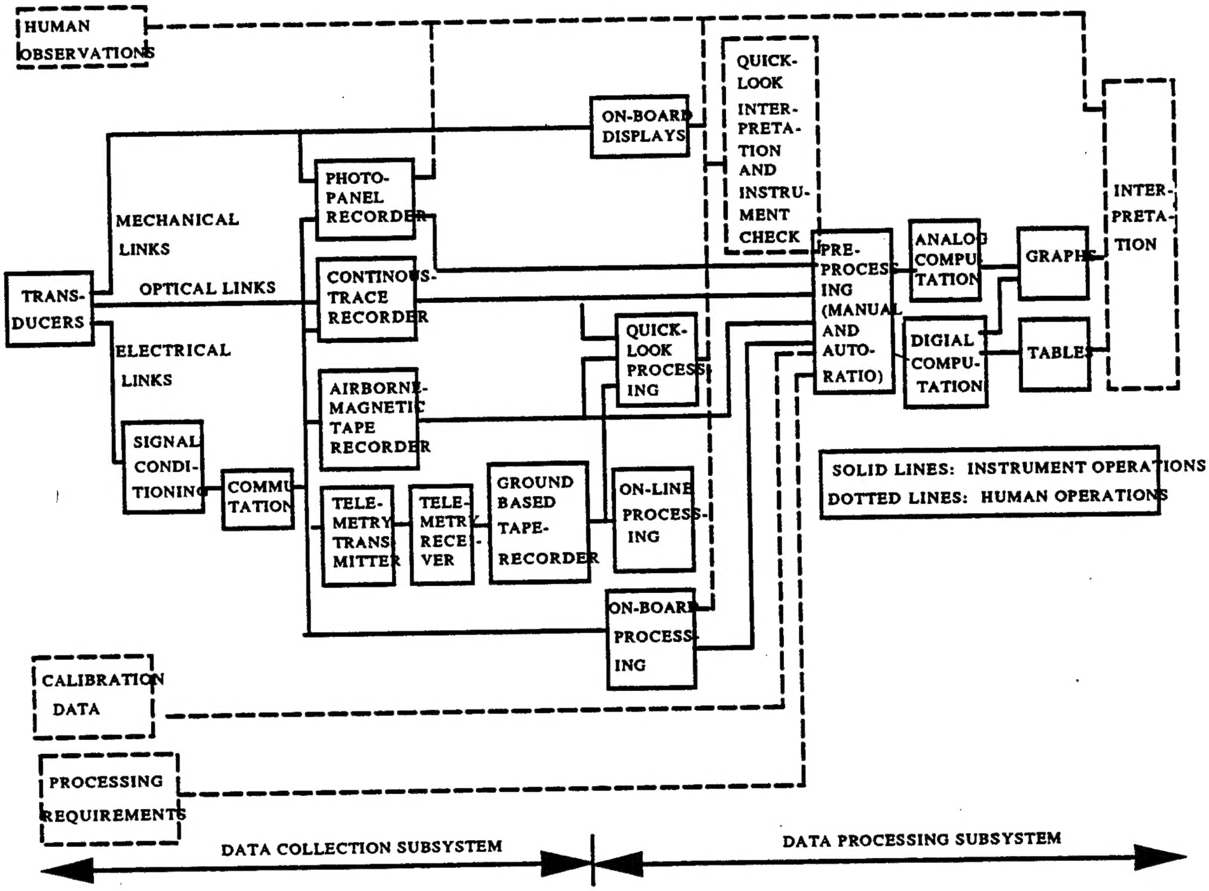


FIGURE 2. BLOCK DIAGRAM OF A FLIGHT TEST INSTRUMENTATION SYSTEM

The data processing subsystem. The task of this subsystem is to convert the collected data to a form which is suitable for analysis. This analysis is usually done in two stages: 1.) a limited analysis is done as quickly as possible, in order to find out whether the tests have gone as planned and whether the data collection equipment has functioned correctly, which is the basis for planning the next flight, and 2.) then a complete analysis provides the test results in their final form. The data processing equipment is generally used in a well protected environment on the ground. In a few cases, part of the analysis is already done in flight. For simple tests involving only a few parameters, data processing can be done by hand. In most flight test systems, however, a large amount of the data processing equipment is used, including one or more computers that utilize complicated software.

An instrumentation engineer begins his work on the data collection subsystem by classifying the entries in the measurements list according to their frequency response and accuracy requirements. These two factors heavily influence the selection of the system. High accuracy requirements in combination with low-frequency requirements and a large number of parameters to be measured usually point towards a digital system. High-frequency response with low accuracy requirements and a smaller number of parameters can often be handled more easily with an analog system, especially if the interpretation of the flight test results can be read directly from a graphical representation of the time history of these parameters. High accuracy and high-frequency response for a large number of parameters will require a complex, costly system. If such a system seems necessary, a careful reconsideration of the purpose of the flight tests may show that the objectives can also be reached with a less complicated system.

By further sorting of the measurements list according to other requirements, such as the period in the test program when the parameter has to be recorded, its priority, etc., the instrumentation engineer will arrive at the number of parameters which must be recorded simultaneously. Here, two approaches are possible: 1.) the data collection system can record all parameters during all flights and the selection of the relevant data for each flight is done in the data processing subsystem, or 2.) the system can be designed to record only the relevant parameters during each flight. If the first approach is used, a larger number of data channels will be required, which generally means that the airborne equipment will occupy more space and

weigh more. It has the advantage that all parameters are available when an unexpected problem occurs. If the second approach is used, different parameters can be recorded alternatively on the same data track so that the physical dimensions of the recording system can often be markedly reduced. It requires, however, a more complicated provision for switching different parameters to the same data channel and it will often require more time during the preflight and postflight checks. In some types of flight tests, there are many parameters which need be measured only a few times during the flight test program. It is often easier to have those parameters read during flight by observers than to reserve separate data tracks for them. Current digital systems not only allow the capability to sample measurements on all tests, but also allow the engineer to select the recorded parameters prior to the flight.

Another important step in the design of flight test instrumentation is the decision whether on-board recording or telelmetry (or both) will be used. This decision is based upon factors such as data turnaround time, aircraft range during flight test, and potential hazard.

It is convenient to break down the data processing into two phases: 1.) the pre-processing phase and 2.) the computation phase. In the pre-processing phase the data remain in the form of time histories of the different parameters, but many kinds of operations are performed on these time histories, such as conversion to a computer-compatible format, selection of channels, filtering, application of calibrations, etc. These operations are all more or less standard for all parameters. In many processing stations (especially those which recieve many different types of inputs such as on-board recordings or telemetry data in different analog and digital formats) a special pre-processing computer is used for all or most of the pre-processing operations. At the end of the pre-processing phase, the data are usually recorded on a magnetic tape or disk which is compatible with the input requirements of standard digital computers.

In the computation phase, data are further processed to a state where they can be used for interpretation of flight results. This is usually done in a standard digital computer that is often shared with other users. In many flight test programs, a preliminary stage of processing is required for quick-look and instrumentation checking. This quick look provides time histories of a limited number of parameters from which the quality of the flight tests can be estimated as a guideline for the planning of the next flight and provides information from

which anomalies in the instrumentation system can be detected. The main requirement for this phase is that the data must be available as soon as possible after the flight. Quick-look data are sometimes obtained by telemetering a limited amount of data to the ground or by a special computer run of the data from the onboard recorders.

Design Considerations. In the design of an instrumentation system for flight testing, a number of aspects must be taken into account which have not yet been discussed in detail. The most important of these are:

1.) Cost

The cost of a flight test instrumentation system is directly related to the requirements imposed. An instrumentation system designed to satisfy only the requirements of a given flight test program will have a basic cost. Below this basic cost, performance of the system will be degraded or its capability considerably diminished. Accuracy has perhaps the most important influence on cost.

The inclusion of optional items may contribute significantly to the overall cost of the system. It must be kept in mind, however, that a system which can also be used for other tests may initially be higher but the overall cost per aircraft may be low.

2.) Redundancy

Where space, weight, and cost allow, it is sometimes advantageous to record critical data on more than one subsystem in order to ensure that the test does not have to be repeated due to an unknown recorder failure. A redundant system can prove to be cost effective based on expensive test resources.

3.) Development or Modification

From an examination of all requirements, a decision must be made regarding how many of the requirements can be satisfied using existing systems or components of those systems. If existing system capabilities prove to be inadequate, then modifications (such as the addition of channels, increase in sampling rate, etc.) can be considered. Modifications are not always successful, but the fact that the accumulated experience gained with the old system can be applied to the new system and is an enormous advantage. With a new system, risks are always involved, especially when the development is first scheduled. Ample time should be reserved to gain experience with a new system and to test it under laboratory and flight conditions.

4.) Schedule

Flight test instrumentation systems are in many cases developed under a very tight schedule. In practice, it is usually very late in the development of an aircraft or of an operational procedure that the measurements list can be made up. A flight test program schedule prepared without consultation with the instrumentation engineer is deficient from the outset. An adequate amount of time in the schedule must be allocated, especially if new systems are to be developed, because many unexpected delays tend to occur. In certain situations, making preliminary program requirements known to the instrumentation engineer will permit enough lead time to begin the development work.

5.) Accuracy

The accuracy of flight test data does not result from the transducer alone but is dependent upon maintaining accuracy throughout the instrumentation system. Verifying overall accuracy adds to the analytical phase of the design in that special tests on all components processing the signal must be made, precision calibration methods must be developed, and the data collection, preprocessing, and processing subsystems must qualify to a more demanding specification. A 5 percent overall accuracy is relatively easy to obtain from analog recording and telemetry systems; 1 percent is a very difficult goal for analog systems. Accuracies of the order of 0.1 or 0.2 percent, which are often requested by flight test engineers, are very difficult to obtain even with digital systems. A very careful consideration of required accuracy must precede the design of any new instrumentation system.

6.) Environmental Qualifications

An important aspect of the overall accuracy is that it must be reached under the environmental conditions present in the aircraft. These include pressure, temperature, vibration and shock, but also include other installation aspects such as electrical and radio interference, power system noise, etc. These latter effects are difficult to estimate before hand. Even though many precautions can be taken during the design phase, only actual tests in the aircraft can show whether these latter effects have succeeded and what further measures need to be taken.

7.) Reliability

Reliability is built into a flight test instrumentation system by using quality components that have undergone a suitable test program and have a flight history similar to that of the intended application. Reliability is further enhanced through good workmanship, inspection, and good system design.

8.) <u>Maintenance</u>

Every system designed and built will require maintenance in its lifetime. Planning for this during system design is essential. Maintenance schedules should be set up early. The judicious selection of places to insert test points for performing electrical checks without disturbing the system will pay for the effort expended during the design. Routine maintenance, such as cleaning tape recorder heads or replacing oscillograph paper, will, of course, be performed without using test points. The real use of such maintenance aids applies when something in the system fails to function. The use of appropriately located test points, built-in or portable test equipment capable of generating calibration signals, and the location of functional portions of subsystems in physically separate modules aids in fault isolation.

9.) <u>Accessibility</u>

The efficiency of maintenance procedures can be impeded if the components in the system are inaccessible when built into the aircraft. The location of test points and adjustable devices which must be readily accessible for maintenance must be planned as to its most advantageous position in the aircraft.

10.) <u>Flexibility</u>

Flexibility is the designed-in capability of an instrumentation system to be changed to meet differing flight test requirements and situations. The objective of flexibility is to minimize the amount of change required in an instrumentation system as a result of large changes in a flight test program and even to adapt itself to other flight test programs in other types of aircraft. Though a "universal" flight test instrumentation system would be both too costly and ineffective, a system designed to satisfy a number of flight test programs and types of aircraft can be cost effective.

14.1.3 CONCLUSION

The subject introduced in this chapter represent the logical first order of business in the design of an instrumentation system in that goals must be established before detailed design can begin. From this point forward, design specialists must decide how best to fulfill the stated requirements. There are many significant technical decisions to be made before a complete system can be realized. Sensors, transducers, signal conditioning techniques, and electronic hardware must undergo careful analysis and laboratory testing. Software must be programmed and tested. In the following sections, the detailed function of instrumentation systems will be discussed.

14.2 TRANSDUCERS

14.2.1 INTRODUCTION

The first element of a measuring channel is the device used to convert the measurand, i.e. acceleration, temperature, pressure, force, etc., into a form which is more suitable for transmission or recording purposes. This device is called a transducer and most generally is designed either to provide an electrical output or, through the use of a suitable mirror arrangement, to reflect a light beam onto a photographic recording medium. Another family of frequently used transducers consists of the mechanical direct-indicating instruments with pointer or numeric indicators. In this family of transducers the transducing and display functions are integrated into a single unit linked by mechanical elements.

The primary emphasis of this section will be placed on transducers with an electrical output although many of the principles and characteristics discussed here apply also to other types of devices. A large variety of physical effects are used for producing the electrical outputs of transducers. The characteristics of these physical effects themselves will not be discussed in detail in this section. They are described in several of the references given. This chapter will concentrate on those characteristics of transducers which are primarily relevant to their role as part of a measuring channel.

For most measurands, there are several transducing principles that can be used. For example, accelerations can be measured by transducers utilizing potentiometers or strain gages, by piezoelectric transducers, by force-balance transducers, etc. Each of these transducer types

has different characteristics of these principles and will be discussed in the discussion on types of transducers.

14.2.2 CHARACTERISTICS OF TRANSDUCERS

Transducer characteristics can be conveniently divided into three groups: input, transfer, and output characteristics. These characteristics mainly determine whether a transducer can be used for a particular measurement. In the final choice of the transducer, other aspects such as environmental conditions, cost, reliability, availability, maintenance and calibration requirements and applicability to other measurements also play important roles.

Input characteristics:

The most important input characteristics are:

- the normal measuring range and the ranges of the environmental parameters. As the errors in many types of transducers are proportional to their range, generally the best accuracy will be obtained if the range of the instrument is equal to or slightly larger than the range of the measured quantity.

- the finesse. This must be appropriate to the measurement, i.e., the affect of the transducer on the physical process being measured must be small with respect to the allowable total error.

- the cross-axis sensitivity. Many transducers which are nominally sensitive only to inputs along one axis of the instrument (such as accelerometers and rate gyroscopes) produce spurious outputs to an input perpendicular to its sensitive axis. An example of cross-axis sensitivity of an accelerometer is shown in Figure 3. The nominal axis of sensitivity is the z-axis, which is perpendicular to the undeflected spring blade. If the spring is deflected by an inertial force acting on the mass along the z-axis, the mass-spring system will also become sensitive to inertial forces along the x-axis. For the relatively small deflections which occur in accelerometers of the type shown in Figure 3, the cross-axis error is proportional to the product of the accelerations in the x and z directions.

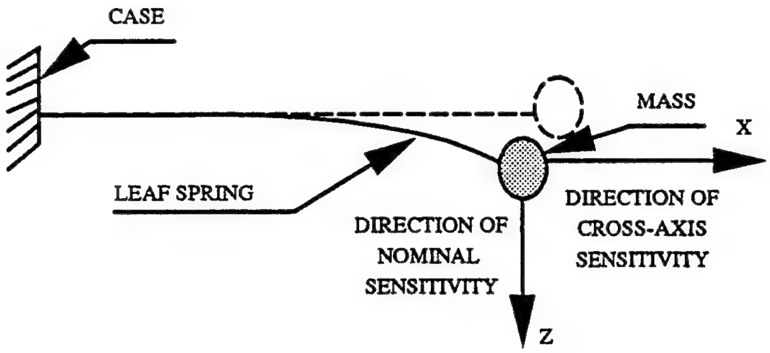


FIGURE 3. CROSS-AXIS EFFECTS IN AN ACCELEROMETER WITH A LEAF SPRING AND MASS

- error in the location or the alignment of the transducer. In many flight tests the location of the transducer relative to the center of gravity of the aircraft and the alignment of the sensitive axis of the transducer relative to the reference axes of the aircraft must be known precisely. Any alignment error will increase the errors in the measurement.

Transfer characteristics:

The transfer characteristics define the relationship between the magnitude of the input quantity and the magnitude of the output quantity of the transducer. These transfer characteristics are determined from the static calibration, the dynamic response characteristics (amplitude and phase) and the associated error distributions and will change with the environmental conditions. Probably the most troublesome aspects of the environment are temperature, shock and vibration, and electromagnetic interference.

The main effects of temperature are zero and/or sensitivity shifts in the output. Some transducers may be compensated for temperature errors by using various electrical and mechanical techniques. Beyond about 250°C, temperature compensation becomes extremely difficult to design and implement. One of the most insidious and little known environmental effects is caused by temperature transients. These transients cause temperature gradients in the instruments which, in turn, can produce temperature errors much larger than those which occur under (quasi) static conditions in the same temperature range. It is practically impossible

for the user to correct the effects of these temperature gradients. Their effect can only be reduced by isolating the transducer as much as possible from the environment.

The effects of shock and vibration are especially difficult to eliminate for inertial transducers such as accelerometers and rate gyros, since they act upon the transducer in the same way as its regular input. For example, an accelerometer used to measure the motion of the center of gravity of an aircraft will also respond to vibrations of its mounting plate relative to the center of gravity (c.g.). If the signal to be measured and the spurious vibration signal are in the same frequency band, it becomes almost impossible to separate them by filtering. If the noise frequency is markedly different from the frequencies of interest, then there are three methods to reduce the spurious vibration signals:

a) Choose a transducer with a frequency response which will transduce the signal of interest without distortion and which will be insensitive to the unwanted frequencies

b) Use a mechanical low-pass filter (vibration isolation mounts) between the source of the excitation and the transducer;

c) Introduce an electrical filter in the output of the transducer.

In general, using a transducer with an optimal frequency response for the measurement is preferable to the other two methods. Locating this type of transducer will not always be possible. One of the problems with mechanical filters is that they often have a non-linear frequency response and will therefore distort the signal of interest. Reasonably linear vibration isolation mounts are available and are used on some inertial platforms. These mounts are, however, costly and have to be specially designed for each transducer.

The use of electrical filters in the output of the transducer can lead to large errors if the amplitude of the vibration is so high that it drives the transducer outside its linear range. If the vibration frequency of the test specimen is much higher than the cutoff frequency of the filter, and is still within the bandwidth of the transducer, the high-frequency vibrations will not be seen at the filtered output. An example of this effect is described in the section on signal conditioning for the case where a closed-loop accelerometer is used to measure aircraft motions. These transducers are chosen because of their inherently high accuracy. They have, however, a bandwidth of the order of 0 to 200 Hz, though the frequency range of the signal of interest is of the order of 0 to 5 Hz. High-frequency vibrations of the mounting plate of

the transducer may then saturate the servo amplifier and thereby cause large distortion. In this case the only way to reduce the errors is to reduce the amplitude of the high-frequency vibration sensed by the transducer. This can only be done by using a mechanical filter between the vibrating mounting plate (the source) and the transducer.

The effect of shock and vibration on non-inertial transducers can be suppressed by the same methods as mentioned above. Here, however, the most practical method is to use anti-vibration mounts.

Other environmental conditions such as pressure, humidity, sand and dust, salt spray and radiation may also have to be considered for specific applications.

Output characteristics:

The output characteristics of a transducer are generally less important than the input and transfer characteristics since they can be appropriately and conveniently modified using signal conditioners (next section). But even so, they are important in the design of the overall data collection system. The main output characteristics are the type of output, the output level and output impedance.

The types of output can be divided into three general categories:

- Analog outputs
- Pulse outputs
- Digital outputs.

Transducers with analog outputs comprise the largest class of transducers in use today. The output voltage is generally classed as being either DC or AC.

Transducers with DC output have a voltage, a current, a charge or an impedance which is a measure of the physical input signal to the transducer. As most recorders and most analog-to-digital converters require DC input signals, some of these transducers can be directly connected to the recorder or encoding device without intervening signal conditioning. In many cases, however, signal conditioning is necessary because voltage amplification, or impedance matching, etc. is necessary.

For transducers with an AC output, the information is contained in either the amplitude, the phase, or the frequency. For transducers with a phase output, a phase reference signal must be available which is often the AC supply voltage to the transducer. The

AC output is usually converted into either a DC output or a pulse output before it is used to drive a recorder, telemetry transmitter or analog-to-digital converter.

The transducers with pulse output represent the information as a pulse rate, a pulse position or a pulse width. The signals in this category can be converted to digital form relatively easily.

The transducers with digital output produce coded output signals which are digital in nature. In some cases the coded signal is available at the output continuously and in others only when the transducer is interrogated by the recording device or telemetry system.

Besides the type of output, there are a number of other electrical output characteristics which are of importance for the matching of the transducer to the recording or telemetry system or for the design of the signal conditioning equipment. The most important of these are:

- Bandwidth
- Output level
- Output power.

The bandwidth of all components of the measuring channel should be at least as broad as the bandwidth of the transducer (with its output filter, if one is used). The output level usually is expressed in terms of the output voltage or current. The output voltages are roughly divided into high-level outputs (0 to 5 volts or higher) and low-level outputs, usually 0 to 20 millivolts. Often different signal conditioning equipment is provided for high-level and low-level outputs. Even if the desired voltage or current is available, the output power that can be taken from the transducer may be insufficient so that power amplification is necessary in the signal conditioner.

14.2.3 TYPES OF TRANSDUCERS

A brief discussion will be given of the characteristics of the more common types of transducers. The main emphasis will be on the transfer and output characteristics because these are particularly important in the overall design of the data collection system.

Table 1 provides a listing of several types of transducers with ranges, accuracies, frequency responses, and types of output typical of those used in many flight test programs.

MEASURAND	TRANSDUCER COMMON NAME	TRANSDUCTION PRINCIPLE	TYPICAL MAXIMUM RANGE	ACCURACY (±)	DATA FREQUENCY RESPONSE (Hz)	OUTPUT		Level	Impedances	REMARKS
						Type		Low High	IV Low 10k IV High 10k	
Acceleration and vibration	Accelerometer	Potentiometric Strain gage Piezoelectric Force balance	± 50 g ± 100 g ± 10,000 g ± 35 g	Medium Medium Medium High	20 200 10,000 20	DC, AC DC, AC AC DC	Voltage Voltage Volt, charge Current	High Low Low / High High	Low Low See remark Low	Must be used with charge amplifiers or with preamplifiers with very high input impedance
Acoustics and sound	Microphone	Capacitive Piezoelectric	180 dB 160 dB	Medium Low /Medium	100,000 10,000	AC AC	Voltage Volt, charge	Low Low / High	High	
Air flow direction	Vanes Aerodynamic probe	Potentiometric Synchro Diff. pressure	± 30° ± 30° ± 30°	Medium Medium Medium	10 10	DC, AC DC	Voltage Voltage	High High (See pressure)	Low Low	
Attitude	Gyroscope	Gyroscopic	± 45°	Medium	10 - 100	(see displacement)				
Attitude rate	Gyroscope	Gyroscopic	± 2000°	Medium	10 - 100	(see displacement)				
Displacement, linear	Potentiometer LVDT	Potentiometric Diff. transfmr.	300 mm 300 mm	Medium Medium	20 20	DC, AC AC	Voltage Volt, phase	High High	Low Low	
Displacement, angular	Potentiometer Synchro Shaft. encoder	Potentiometric Inductive	3600 360 360	Medium High High	20 20 20	DC, AC AC Digital	Voltage Voltage	High High	Low Low	
Flow rate, vol Flow rate, mass	Flow Meter	Turbine	3,000 gal/hr 20,000 lbs/hr	Medium		Pulse Rate		Low	Low	
Strain, loads	Strain gage	Resistive	6,000 μ in/in	Low	10,000	DC, AC	Voltage	Low	Low	
Liquid level		Capacitive Nuclear	12 ft 6 ft	Medium Medium		AC Pulse	Voltage	Low	High	
Pressure	Pressure transducer	Potentiometric Strain gage Capacitive Piezoelectric	500 psi; 350 N/cm² 5,000 psi; 3500 N/cm² 1000 psi; 700 N/cm² 10,000 psi; 7000 N/cm²	Medium Medium Med/High Medium	20 10,000 100,000 10,000	DC, AC DC, AC AC AC	Voltage Voltage Voltage Volt, charge	Low Low High See remark	Low Low High See remark	See remark acceleration and vibration
Rotary speed	Tacho generator	Inductive	100 % RPM	Medium		Frequency		Low	Low	
Temperature	Resis. thermom. Thermister Thermocouple	Resistive Resistive Thermoelectric	1000 °C 300 °C 1200 °C	High High Medium	20 200 2	DC, AC DC, AC DC	Voltage Voltage Voltage	Low/High Low/High Low	Low Low Low	

± Low accuracy : error > 3% FS. medium accuracy : error < 1-3% FS. high accuracy : error < 1% FS.

Many other types are available for special applications. It should be noted that variations in accuracy and other characteristics are possible within each category in the list.

In the following discussions the transducer types have been divided into four categories, each of which will be discussed separately. These categories are the active analog, passive analog, pulse and frequency generating, and digital.

14.2.4 ACTIVE ANALOG TRANSDUCERS

Active or self-generating transducers require no external source of power or excitation. The most common types of active analog transducers used in flight test applications are piezoelectric transducers.

Piezoelectric transducers operate on the principle that a voltage is generated in certain crystal materials when they are subjected to mechanical forces or stresses along specific planes. Figure 4a shows a section through a transducer where the acceleration produces a shear force in the piezoelectric material. In Figure 4b the acceleration force produces a compression. Piezoelectric transducers are basically charge generating devices with an output impedance of several hundred megaohms. When used as voltage generators, they must be connected with very short cables to special high-impedance voltage amplifiers. Calibration of the piezoelectric transducer has to be done after installation, since small variations in the capacitance of the cable could cause significant changes in the calibration. The use of charge amplifiers minimizes the effects of cable capacitance, noise, etc.

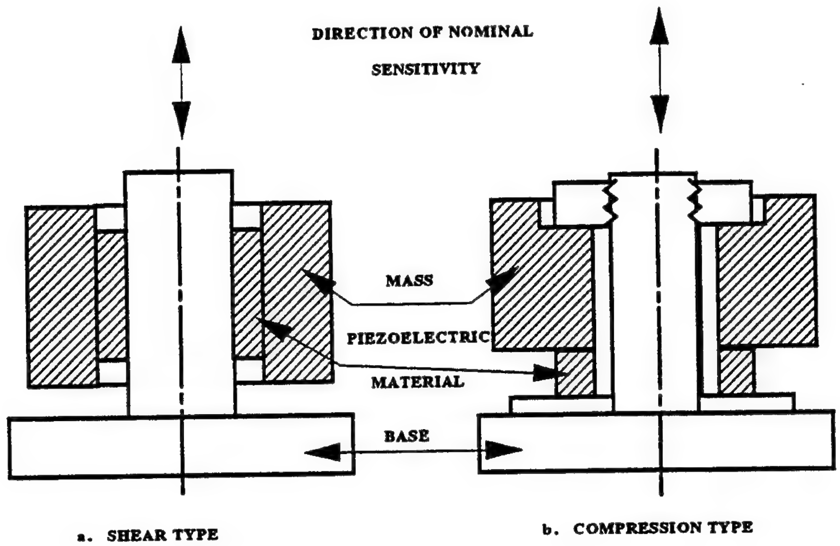


FIGURE 4. TWO TYPES OF PIEZOELECTRIC ACCELERATION TRANSDUCERS

The outstanding characteristics of piezoelectric transducers are their large range (up to 10,000 g), extremely high natural frequency (about 30,000 Hz), and small size and weight. They are used extensively for the measurement of high-frequency vibrations, but they do not respond well to low-frequency vibrations. The low-frequency cutoff point of these devices is 10 Hz or somewhat lower, depending on the preamplifier used.

Thermoelectric transducers utilize thermocouples, which consist of two dissimilar metal wires whose ends are connected together. When the dissimilar junctions are subjected to different temperatures, a voltage is produced. The magnitude of the voltage depends upon the temperature difference across the junction and the materials of the conductors. The most common types of thermocoupoles used in flight testing are copper-constantan, chromel-alumel, iron-constantan and platinum-platinum/rhodium.

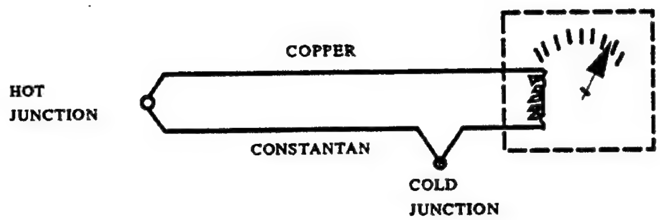


FIGURE 5. COPPER-CONSTANTAN THERMOCOUPLE CIRCUIT

Thermocouples are mainly used for the measurement of high temperatures, for example, on aircraft engines. Their output voltage is normally in the range of 0 to about 60 millivolts (mv) and typically they have an output resistance of a few ohms. Thermocouples require either a reference temperature device for maintaining a constant temperature at the cold junction or a mechanical or an electrical compensation device for cold-junction temperature changes. Special bonded-foil thermocouples are used for measuring surface temperatures.

Magnetoelectric transducers are instruments of the induction generator type, in which the motion of a conductor or coil in a permanent magnetic field induce a voltage in the coil. The output voltage of the magnetoelectric transducer is proportional to its magnetic field strength, the number of turns in the coil, and the velocity of the coil relative to the field. Common applications of this effect are the AC and the DC tachometers used in measuring rotary velocity. The magnetoelectric effect is also used for generating pulses.

Photoelectric transducers produce a voltage which is roughly proportional to the light energy falling on a photoelectrical cell and are mainly used for on-off type measurements, such a digital shaft encoders.

14.2.5 PASSIVE ANALOG TRANSDUCERS

The physical input varies the impedance in these transducers. An external power source is required for producing an output voltage or current. In many of these transducers (potentiometers, differential transformers, and synchros) two or three output voltages are produced, the ratio of which contains the information. Other types (resistance thermometers, variable self-inductances, variable capacitances), which have only a single variable impedance, are often used in bridge circuits or in variable-frequency oscillators.

Variable resistance transducers:

Potentiometers. The value of the output of a potentiometer is determined by the mechanical rotation or the linear displacement of a sliding contact. The resistance element usually consists of a wire wound around a form, or a metallic, carbon or conductive plastic film deposited on a nonconducting base. The resolution of wire-wound potentiometers is limited by the number of wires used; the resolution of metallic film potentiometers is unlimited.

Potentiometers are extensively used in flight testing. Their main advantage is that they can give high-level DC outputs which can be easily filtered and which can be used without amplification. Potentiometers must, however, be applied with care because they can be subject to a number of problems:

- Friction always exists between the resistance material and the wiper. Though this friction can be quite small for high quality potentiometers, it limits the attainable accuracy in cases where only small forces are available, as in low-range pressure transducers.

- Vibrations and accelerations may affect the contact pressure of the wiper, resulting in output failures. These failures can sometimes be reduced by choosing the best orientation for the potentiometer with respect to the main direction of the vibration.

- Wear of the resistance element can be a problem, especially if the wiper moves in the same region for a long time. Wear can cause nonlinearities well before a final breakdown occurs.

- Film type potentiometers can have a non-linear characteristic, particularly near the end of their range and near taps. This nonlinearity also causes production of only a very small wiper current.

Potentiometers are used for the direct measurement of linear and angular displacement. They are also used in transducers to measure displacements derived from physical input quantities such as pressure, acceleration, force, and rate gyro deflection.

Strain gages. The wire strain gage and the foil strain gage are based on the principle that the resistance of a wire or foil changes in a reproducible way when stretched within their elastic limits. Two types of strain gages are used extensively in flight testing: bonded-wire or foil strain gages (Figure 6). The wire or foil is bonded to a thin sheet of backing material,

which in turn is cemented to the structure to be tested. In order to optimize the sensitivity of the gage for particular applications, the sensitive element can be formed into different patterns. For example, the strain gages shown in Figure 6 measure strains in a single direction. Other types of strain gages (rosette types) are available for measuring omni-directional strains. These consist of several strain gages of the type shown in Figure 6, bonded to the same base at predetermined angles with respect to each other. For measuring membrane deflections, gages of spiral shape are sometimes used. Bonded strain gages are used by themselves as transducers for measuring strains in structures, and are also incorporated in the design of other types of transducers (e.g. pressure gages).

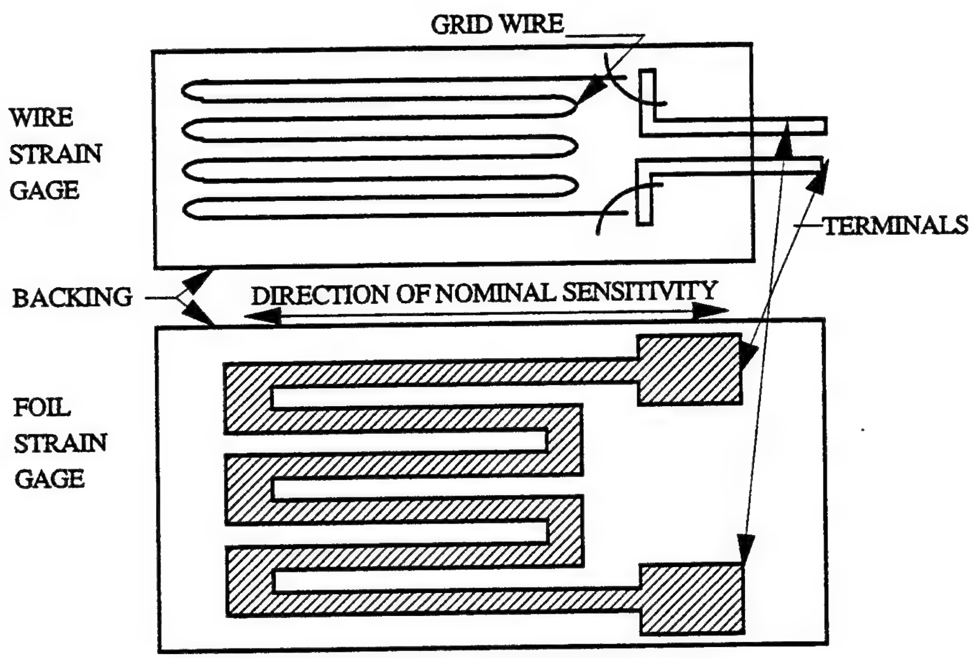


FIGURE 6. FOIL AND WIRE STRAIN GAGES

A relatively new development is the semiconductor strain gage, which operates on the piezoresistive effect. The gage material is a single crystal of doped silicon. The principal advantage of this type of strain gage is its high sensitivity (over 50 times greater than for the wire type). Its temperature sensitivity is, however, much larger than in metal strain gages so there is often little gain in using them when temperature can change considerably. They are used in transducers where effective means for temperature compensation can be incorporated during manufacture.

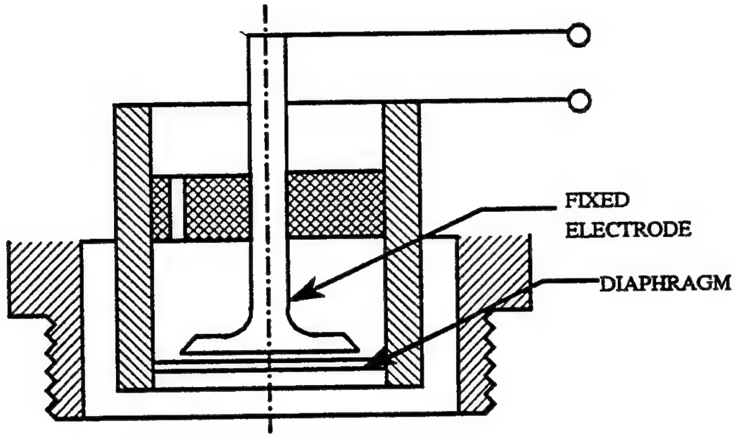
Resistance thermometers. Two types of resistance thermometers are widely used in flight testing: the metal wire resistance thermometer and the thermistor.

The metal resistance thermometers are usually made of nickel or platinum wire. The reproducibility is very good and the calibration is nearly linear over a wide temperature range. Some types can be used to temperatures of 1500°C. There are two basic configurations: the bulb type and the surface type. The standard bulb type thermometer has a metal protection tube around the wire. They are relatively large and have a slow response. Special types, such as those used in many stagnation temperature probes, are somewhat smaller and have their wire directly exposed to the air. In these thermometers, time constants of a few seconds can be attained. Their output voltage is generally larger than for strain gages and can often be used without amplification. When designing measuring circuits for resistance temperature elements, the maximum allowable self-heating of the element must be taken into account. Elements for measuring surface temperatures consist of a fine wire grid bonded to a backing material and are similar in construction to strain gages. They are cemented to the surface where the temperature measurement is to be made.

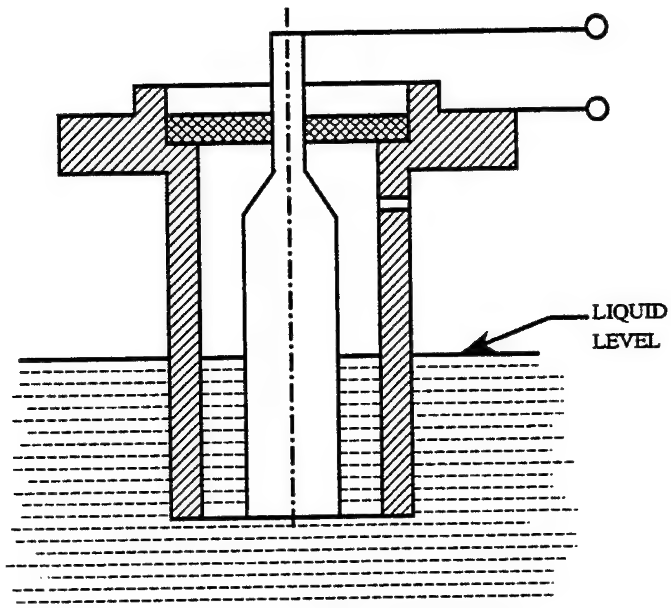
Thermistors incorporate a resistance element made of a semiconductor material. They can be made very small in size, thus allowing for a relatively high frequency response. Many types of thermistors have negative temperature coefficients. The relationship between the thermistor's resistance and temperature usually is non-linear.

Variable capacitance transducers:

In variable capacitance transducers the effective area of two parallel plates, the separation between them, and the dielectric strength of the material separating them determine the capacitance. Common examples of transducers using a change of plate spacing are the condenser microphone and the capacitive pressure transducer (Figure 7a). Variation in the dielectric is generally used to measure fuel level (Figure 7b).



a. CAPACITIVE PRESSURE TRANSDUCER



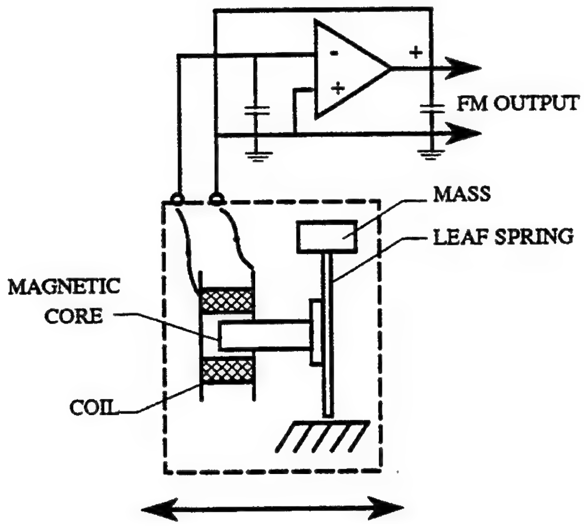
b. CAPACITIVE FUEL LEVEL TRANSDUCER

FIGURE 7. CAPACITIVE TRANSDUCERS

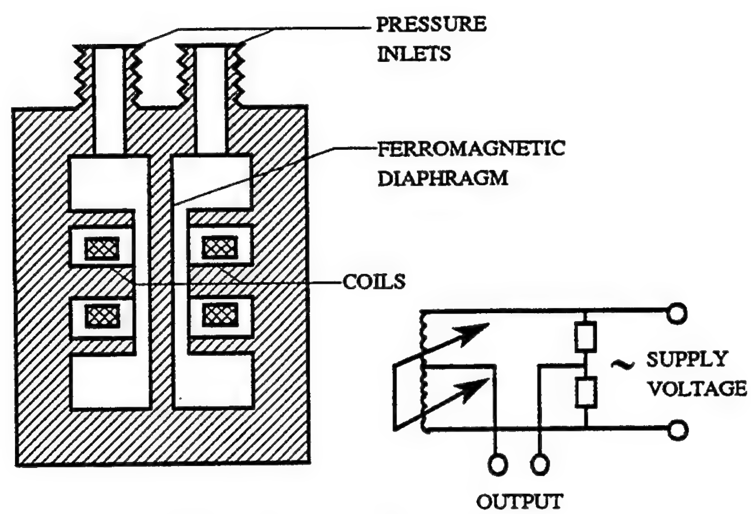
Advantages of capacitive transducers include their small size, their excellent high-frequency response, and their ability to withstand high temperatures. Disadvantages include their temperature sensitivity and their high-impedance output, which requires rather complex signal conditioning circuitry.

Variable inductance transducers:

In variable self-inductance transducers the position of a coil determines the self-inductance of the coil. Inductance type transducers are available for a large number of inputs which produce a linear displacement, such as pressure, acceleration, force, etc. They are low-impedance devices which produce relatively high output signals. They are often used for analog FM recording or telemetry. The coil in these tranducers forms part of the oscillator circuit which produces the frequency-modulated signal (Figure 8a). They are also in bridge circuits. Figure 8b shows a bridge circuit with two self-inductances one of which increases while the other decreases with the measurand. These transducers can be made very small and can operate at relatively high temperatures.



a. VARIABLE SELF-INDUCTANCE ACCELERATION TRANSDUCER IN AN OSCILLATOR CIRCUIT



b. VARIABLE SELF-INDUCTANCE PRESSURE TRANSDUCER IN A BRIDGE CIRCUIT

FIGURE 8. INDUCTIVE TRANSDUCERS

Synchros:

Generally, synchros are used for positioning by electrical means the shaft in a repeater to the same angular position as another shaft on which the transmitter is mounted. In their normal use, the output is an angular position of a rotor, not an electrical output. As such,

they are used in flight testing for the transmission of angular positions to pointer instruments. But their main importance in flight testing is in a different application. Since synchros are extensively used in the normal operational equipment of the aircraft, many measurements can be obtained by tapping the electrical signal of these operational circuits, thereby precluding the need to install separate transducers. Rather complex signal conditioning circuits are required, but nevertheless this method is often more convenient than the use of additional transducers.

There are two general classes of synchros: the torque type and the control type. In the torque synchro circuits (Figure 9a), the rotors of the torque transmitter and the torque receiver are both connected to the AC supply voltage. If the two rotors are not aligned, a current will be generated in the stator circuit which moves the torque receiver rotor to its correct shaft position. The positioning accuracy of the receiver under static conditions is about 0.25 degrees (i.e. better than 0.1% of the 360 degree full scale value). Due to the relatively low power, the large inertia of the torque-receiver rotor and the slip-ring friction in the receiver, frequency response of the torque synchro is rather poor. An electrical measurement of the transmitter position can be obtained by tapping the stator wires using high-impedance circuits. The rotor voltage is used as a reference in some signal conditioners.

In control synchro circuits (Figure 9b), only the rotor of the control transmitter is connected to the supply voltage. Currents in the stator circuit induce a voltage in the rotor of a control transformer which is amplified and fed to a servo motor which drives the control-transformer rotor to its correct position. The accuracy of the alignment of the rotor can be much better than for torque synchros. The output of the control synchro chain is also a shaft position. If an electrical output of a control synchro chain is required, this output can be taken from the stator wires as in Figure 9a. It is, however, better and more accurate to mount an electrical transducer (e.g. a potentiometer or a digital shaft encoder) on the axis of the servo motor and to use its output.

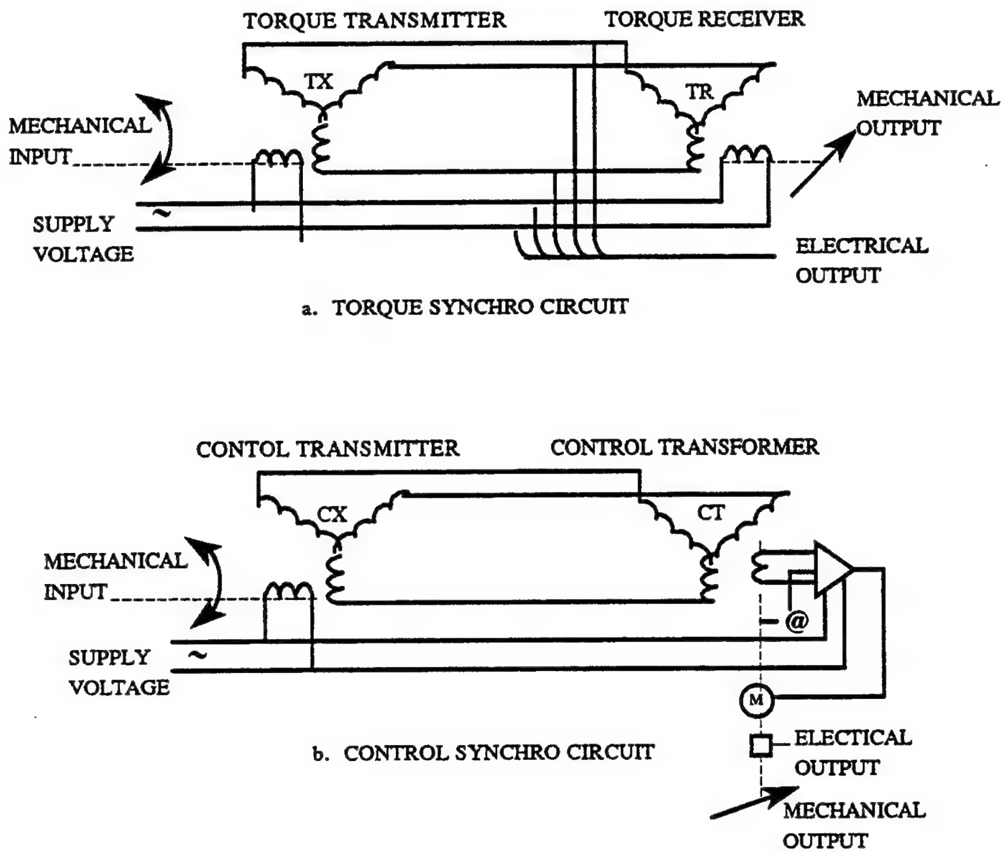


FIGURE 9. SYNCHRO CIRCUITS

14.2.6 PULSE AND FREQUENCY GENERATING TRANSDUCERS

For pulse-generating transducers the information is represented as a continuously variable pulse repetition rate. Frequency generating transducers produce sinusoidal outputs with a frequency proportional to the value of the input to the transducer. In the majority of flight test applications, this frequency is transformed in the signal conditioning circuit to a pulse rate by amplification and clipping. Frequency outputs of pulse generating transducers can be used in many ways, but they are generally transformed into a train of pulses. Pulse and frequency generating transducers are analog transducers, and their output can be very easily transformed into a digital output using a counter. They are, therefore, sometimes classified as semi-digital transducers.

Pulse-generating transducers:

Most pulse-generating transducers produce a series of voltage or current pulses whose rate is proportional to the value of the physical parameter measured. The most common types of pulse transducers operate upon the magnetoelectric or the photoelectric principles.

The magnetoelectric sensor consists of a coil with a small permanent magnet. When the field of the magnet is disturbed momentarily by the movement of a piece of the ferromagnetic material passing it, a pulse is generated in the coil. This principle is often used for the measurement of rotation speeds in engines and in turbine-type flow-rate transducers (Figure 10). For each revolution one or more pulses are induced in the sensor.

The photoelectric or photoresistive sensors are also used for detecting rates of rotation. The pulses are produced by periodically interrupting a light beam from a lamp to a photoelectric cell or a photoresistance. This principle is not often used in flight testing. One application is in tape recorders to detect whether or not the tape is running.

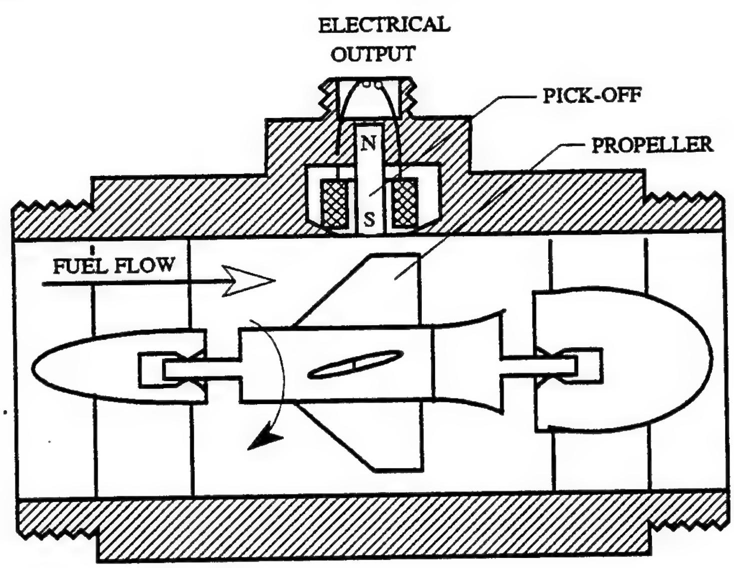


FIGURE 10. PULSE-GENERATED FUEL FLOW TRANSDUCER

Frequency-generating transducers:

Many types of frequency-generating transducers are used in flight testing. One is the AC tachometer, which has an output proportional in both frequency and amplitude to the angular velocity of the shaft to which it is attached. Other types of frequency-generating transducers used in flight tests include the variable self-inductance transducers and the

capacitive transducers when used as an element in a variable frequency oscillator. In another type, the vibrating wire transducer, the measurand changes the tension of a vibrating wire, and thereby its vibration frequency. Part of the output signal is fed back through a servo amplifier to maintain the oscillation. The same feedback principle is also used for tuning forks and crystals which are used in timing circuits.

14.2.7 DIGITAL TRANSDUCERS

The digital transducers produce a digitally coded output. The most common type of digital transducer uses a shaft-position encoder such as shown in Figure 11. The same principle is also employed in linear-scale encoders, which can be used to encode rectilinear motions. The digital encoders may be grouped into two major categories: the brush and the brushless types.

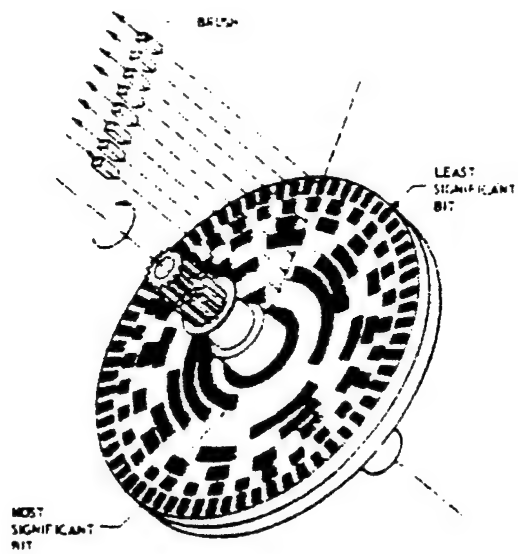


FIGURE 11. SEVEN-BIT BRUSH-TYPE DIGITAL ENCODER

Figure 11 shows a brush-type encoder. The disk is composed of a series of conducting and non-conducting areas on several concentric rings, one ring for each bit in the output. The conductive areas are all connected to a voltage source and a digital "1" bit is produced by the current which flows through a brush when it contacts a conducting area. No current flows through the brush when it is in contact with a non-conducting area and the digital "0" bit is produced.

The brush-type encoders are rather sensitive to vibration, which may affect the contact between the brushes and the disk. This effect of vibration is somewhat less in brushless encoders. The disks are similar in layout, but the detection of a "1" is done by a magnetic, capacitive, or optical sensor.

There are also some digital transducers which are analog transducers with a built-in electronic digitizer, functioning on the same principle as the analog-to-digital converters described under signal conditioning.

Digital transducers are not used extensively in flight testing at the present time, because the effects of vibration have not been completely overcome (at least for the encoder-types of transducers), and because problems still exist with their high-frequency response. Another reason for not using digital transducers is that they are very costly and are only available for a limited number of transducer types. Since analog-to-digital conversions must be provided for the transducers which have only analog outputs, it is generally more economical to avoid using these transducers.

14.3 CALIBRATION

14.3.1 INTRODUCTION

Measurement can be defined as the process of comparing the magnitude or intensity of a physical quantity to a reference value or standard in order to determine a numerical value of that physical quantity. In the early times standards were usually defined in such a way that everyone who wanted to make a measurement had direct access to the standards. For instance, standards of length were the width of a thumb, the length of a foot, the distance covered in a stride, etc. As greater accuracy became necessary and more physical quantities had

to be measured, international standards were adopted. Standards in different countries were either compared periodically to each other or the methods for deriving them were so exactly prescribed that they could be reproduced with sufficient accuracy. This development led to the establishment in 1875 of the International Bureau of Weights and Measures at Severes, France. The standards preserved there are the international reference standards or primary standards to which all other standards can be compared.

From these primary standards a complex echelon of subordinate standards is derived. Each technically developed country has its Standards Bureau or Laboratory, which has secondary standards that are directly derived from the primary standards. Many major industries and research laboratories have tertiary standards which are derived from the secondary standards. The lower standards are all periodically compared to a standard one order higher to determine their validity as a standard. The measuring instrument is at the lowest level of this network.

Calibration is the process of determining the measuring characteristics of an individual instrument or measuring chain, with the accuracy required for a particular application, using suitable standards as a referenced. In general, previous knowledge of the general characteristics of the instrument type will have been available when the instrument was selected for the application. The calibration will then establish precisely the relation between input and output of the particular instrument and will be the basis for a check of its accuracy.

The calibration engineer uses the information provided by the calibrations to establish:

- the proper functioning of each component
- the relationship between the physical input and output of the complete measuring chain, which is used to convert the measured data to engineering units during processing, and
- the accuracy with which the measuring system follows this relation.

14.3.2 THE SCOPE OF CALIBRATION

Complete calibrations:

In any practical application the output of a measuring channel will not only be determined by the magnitude of the parameter which it should nominally measure but also by the magnitudes of physical quantities other than the one that must be measured. A measure-

ment of a pressure difference, for instance, may be influenced by the pressure level at which the measurement is made, the temperatures of the different elements for the measuring chain, the acceleration to which the transducer is subjected, the supply voltage, etc. If an accurate measurement is to be made, these influencing quantities should also be measured simultaneously with the measurement of the input parameter. A calibration then must also include a determination of the sensitivity of the output of the measuring system to each of these environmental parameters.

A complete calibration (a complete determination of the measuring characteristics of a particular instrument for a particular application) should not only be concerned with the parameter which is nominally measured by the measuring channel, but also with the other parameters which can affect the output. As the calibration relating to the nominal input parameter is usually broken down into a static and a dynamic calibration, a complete calibration usually consists of three parts:

- A static calibration related to the nominal input parameter. This gives the relationship between the input value of this parameter and the output of the instrument or component, provided the input parameter is varied so slowly that the dynamic characteristics of the measuring system do not affect the output.

- A dynamic calibration which usually gives, as a function of frequency, the amplitude ratio (i.e. the ratio between the measured output amplitude and the value which this amplitude should have according to the static calibration) and the phase angle between the input and output.

- Environmental calibrations include all environmental parameters which can affect the output. As the sensitivity of the output to these environmental parameters usually is much less than the sensitivity to the nominal input parameter, the accuracy required for these calibrations often is not very high.

In each calibration, whether static, dynamic, or environmental, a standard should be used to measure the input parameter and another standard to measure the value of the output. The accuracy required of these standards must be derived from the accuracy specified for the measurement.

Limited calibrations:

A complete calibration as described earlier will in general be a complex and time consuming exercise. In practice the procedure is usually simplified considerably, but limited calibrations can only be done under specific circumstances. These are:

- that the ranges and frequency spectra of the nominal input parameter and of the environmental parameters for the particular application are specified to a sufficient degree,
- that previous knowledge of the measuring characteristics of the instrument is available, either from previous use and calibration of the instrument or from manufacturer's specifications,
- that the accuracy of the particular measurement for which the calibration must be made is well specified.

If these requirements are met, the calibration engineer may decide that certain parts of the complete calibration procedure need not be executed for a particular test. Such a decision can only be made if the calibration engineer is satisfied that his previous knowledge is applicable to the specific circumstances of the test within the specified accuracy requirements. When making this judgement it must be kept in mind that the "previous knowledge" may not be applicable to the circumstances of the test for which the calibration is made. Some possible reasons for this are:

- the environmental conditions during previous calibrations differed from those of the test (the manufacturer's test conditions are frequently not fully specified), or
- the characteristics of the instrument may have changed since its last calibration because of aging or damage.

The static calibration will only be deleted on rare occasions. Even when a very low measuring accuracy is required, it will generally be better to run a static calibration because this will at least provide assurance that the instrument functions properly. Dynamic calibrations and many or all environmental calibrations can often be deleted or can be performed at considerably longer intervals than the static calibrations. After a major repair of an instrument a more complex calibration will often be required.

14.3.3 STATIC CALIBRATION

Static calibration of the instrument against its nominal input is performed far more often than any other type of calibration. When an instrument is selected for a particular measurement, it is usually chosen in such a way that the dynamic characteristics will not have a large influence on the static calibration and correction for dynamic effects can be based on much less frequently executed dynamic calibrations.

The choice of the calibration standard has already been discussed in some detail. When using an available calibration system for a new instrument, great care must be taken to ensure that no errors are introduced into the calibration by <u>an interaction between the instrument being calibrated and the standards which are being used as a reference</u>. The interaction which may occur is often quite subtle and difficult to recognize, but the errors which can be introduced may be of significant magnitude. This is one aspect of the concept of "<u>finesse</u>". Examples of calibration interactions include excessive loading of an electrical standard and temperature effects due to self-heating by electrical currents.

In general, the static calibration is performed by applying fixed incremental values of the measured parameter to the instrument and measuring the calibrated and traceable standard of sufficient accuracy. For measuring systems with an electrical output a properly calibrated indicator must be chosen so that it provides the same load to the output circuit as is used in the aircraft. If the calibration data are directly processed by a digital computer, the output can be measured by an instrument which directly provides a digital output in a format suitable for the computer.

The <u>number of points</u> used in the calibration must be sufficient to establish the complete calibration curve with the required accuracy. Here it is important that the final accuracy of the calibration be kept in mind. In cases where a high degree of accuracy is required it may be necessary to use a relatively large number of points. This is especially true when the input-output relationship is suspected or known to be <u>non-linear</u>. On the other hand, if the instrument being calibrated is considered to be much more accurate than the total requirements, very few points may be sufficient to provide the needed confidence. This can in some cases mean that the calibration equipment can be simplified. For example, for some accelerometers it may be sufficient to measure points at +1 g, 0 g and -1 g, which can be done

using a sufficiently horizontal table and a simple bracket in which case the more expensive equipment necessary for measuring other points will not be required.

In some measuring systems environmental parameters, like the supply voltage or the FM carrier frequency , can produce shifts in the zero point of the calibration or in its average sensitivity without significantly affecting the shape of the calibration curve. In such cases one or two fixed voltage inputs are often recorded or telemetered once in every measurement cycle in order to provide a basis for correction. Such measurements are often called "calibration points" or "autocal". It must be stressed that this technique does not obviate the requirement for a normal calibration of each measuring channel and does not reduce the number of points required in the calibration.

Another important point in calibration is hysteresis. If hysteresis occurs, it is necessary to calibrate the instrument first with increasing values of the measuring parameter and then with decreasing values, and to take at each point the average of the two. It must be kept in mind, however, that the magnitude of the hysteresis may depend on the range used. If during the flight test the input parameter will vary only over part of the total range of the instrument, it will be better to calibrate only over that range. If the hysteresis error is large with respect to the allowable total error, it is sometimes necessary to simulate the expected time history of the measurement during the calibration. Some types of hysteresis, such as that caused by backlash in gears, will not depend on the complete previous time history of the measurement, but will depend only on the direction in which the input parameter changed at the particular moment of measurement. Therefore, it is important for the calibration engineer to understand the nature of the hysteresis before setting up his calibration program. The hysteresis may also depend on the vibration level to which the instrument is subjected. During calibrations where hysteresis is important, the instrument should be subjected to the same type of vibration as is expected during the flight test.

14.3.4 DYNAMIC CALIBRATION

The objective of a dynamic calibration is to determine the dynamic characteristics of an instrument or measurement system. The dynamic characteristics are usually given as a function of amplitude ratio and the phase angle with respect to frequency.

In many cases the instruments for a particular measurement have been chosen so that the dynamic effects of that instrument can be neglected for the range of frequencies which will occur during the flight test. Then the dynamic calibration is only used to verify that this assumption is true. There are many measurements in which sufficient accuracy can only be obtained if a correction is made for the dynamic characteristics. If this is the case, it is very desirable that the measuring system be dynamically linear, i.e., that its response can be described by a linear differential equation.

For dynamically non-linear systems, the correction becomes a very complex and arduous task. Fortunately, most instrument systems designed for dynamic use follow a linear differential equation sufficiently closely. Linearity must, however, be verified during the calibration process. The easiest method to verify linearity is to apply the method of sinusoidal excitation described below with several amplitude values at each frequency. If the amplitude ratio is independent of the amplitude, it can be assumed that the system is dynamically linear.

It is essential that, during the application of a dynamic calibration, not only is the amplitude ratio taken into account, but also the phase angle. In systems with a constant group delay the phase angle will cause a constant time delay between input and output; if the group delay is not constant over the range of frequencies contained in the signal, phase distortion will occur. It is, therefore, essential that during a dynamic calibration both the amplitude ratio and the phase angle be measured.

There are two principal methods for determining the dynamic response of a measuring system:

1) Sinusoidal excitation

In this method the instrument is subjected to a sinusoidally varying input, the frequency of which can be varied over the complete dynamic range of interest. The amplitude ratio between input and output and the phase angle between these two are then measured directly at a number of frequencies. From these measurements, plots of the amplitude ratio and the phase angle versus frequency can be made.

2) Pulse excitation

In this method the instrument is subjected to either a step function change in the input or to a sharp input pulse. In this technique particular care must be exercised to avoid saturating or over-driving the instrument at any frequency. By utilizing Fourier analysis techniques on the output, the amplitude ratio and the phase angle at each frequency can then be calculated.

The excitation of signal conditioning networks or other components of a purely electrical nature is usually not too difficult because generators of electrical sine waves and pulses are readily available. Devices for accurate dynamic excitation of other physical parameters are much more difficult to obtain. Methods of dynamic stimulation of linear and angular displacements and accelerations, and of forces and moments, have been available for some time, but generators for stimulating high amplitudes and low frequencies (below about 15 Hz) are still difficult to obtain.

14.3.5 CALIBRATION OF ENVIRONMENTAL PARAMETERS

A complete and comprehensive calibration of a test instrument or measurement system must take into account the environment in which the instrument is to be used and the effect that these extraneous influences have on the accuracy of the measurement. Some of the more common environmental parameters which are probable sources of error are temperature, pressure, acceleration, vibration, supply voltage and electromagnetic radiation. To establish confidence in the ability of a particular instrument to accurately perform its designated task, an understanding of the affect of these environmental parameters is essential.

The reason for making an environmental calibration can be threefold:

- To verify that built-in correction features, such as temperature compensation, are functioning properly according to the manufacturer's specifications,

- To establish that the environmental effects are negligible, and

- To determine the sensitivity of the instrument for the environmental parameter in order to provide information for the correction of the measured results.

In this latter case it must be recognized that a separate measurement of each environmental parameters must be made in order to provide information for the proper correction factor of the measured results. Also in this latter case it must be recognized that a separate

measurement of each environmental parameter during the flight test is necessary in order to apply the correction.

Naturally, not every calibration of an instrument requires actual environmental testing of all or even any of the extraneous parameters which may be encountered, but certainly these parameters must be given consideration. The actual flight test environment, prior evaluation tests, previous experience, or an understanding of the construction of the instrument may provide the confidence needed to negate the requirement for actual environmental tests.

As a general rule, the sensitivity of an instrument to its environmental parameters is much less than the sensitivity to the primary input. Therefore the accuracy with which these environmental parameters must be generated is generally less than that for the main input.

14.3.6 THE OVERALL CALIBRATION OF A MEASURING CHANNEL

The ultimate purpose of the calibration program is to provide the information needed to convert the measuring results to engineering units and to provide a basis for a final check on the accuracy of the measurements. For both purposes, the overall (end-to-end) calibration of each measuring channel must be known.

In modern flight testing, such overall calibrations of the channel are usually not made directly. The overall calibration is usually determined from a mathematical combination of calibrations of the components of the measuring channels. There are two main reasons for this component calibration procedure. 1) A new complex overall calibration of many channels may be required if one single component, for example an analog-to-digital converter used for many channels, has to be replaced. If the concept of component calibrations is used, only a calibration of this single unit will be necessary. 2) An overall recalibration of one channel may require that a large part of the total data collection system is transported to the calibration laboratory, with consequent risk of damage to some other components. If the overall calibration is performed in the aircraft, less accurate transportable calibration standards will have to be used.

Under some circumstances, however, the individual component calibration procedure is either impractical or impossible, requiring that an overall calibration of the complete measurement channel be done from the transducer to recorder or telemetry output. An

overall calibration is the safest method of calibration because it will include the effects of mismatches between adjacent components in the measuring chain or interference that may exist between one component and another. Finding mismatches may not be possible if each component is calibrated separately. In cases where some form of feedback between separate components of the aircraft structure (such as a control surface) must be included, an overall system calibration must be performed on the aircraft after final installation.

Combining static and dynamic component calibrations into an overall calibration of one measuring channel requires careful consideration. Static calibration involves the multiplication of the input/output ratios corresponding to each calibration point of the physical input parameter after all necessary corrections for environmental effects have been applied to the calibration point. When dynamic effects are considered, the amplitude characteristic with the lowest break frequency will mainly determine the overall amplitude response of the measuring channel. In both the static and dynamic calibration, the phase response of the other components may, however, affect the overall phase shift characteristic of the measuring channel. In-flight checks or "calibrations" to establish certain environmental effects such as aircraft supply voltage or shifts in FM center frequency may also be considered within the scope of the determination of the overall calibration.

14.4 SIGNAL CONDITIONING

14.4.1 INTRODUCTION

The output signal from a transducer is usually modified several times before it is in the final form in which it can be subjected to computation. Examples of such modifying operations are amplification, filtering, sampling, digitizing, data compression, digital format conversion, carrier frequency modulation, and the application of calibrations. In principle, these operations do not change the essential information contained in the signal. Each operation is done in order to adapt the signal to the input requirements of the next unit in the measuring chain. In a broader sense all operations between the transducer and the computer that is used for the final analysis could be regarded as signal conditioning.

In flight test instrumentation language the expression "signal conditioning" is generally reserved to indicate the modifying operations done on-board the aircraft. This expression is

used to indicate the signal modifications that occur between the transducer and the input stage of the recording or telemetry system.

In a few cases, operations like filtering are done on the physical input signal before it enters the transducers. This is usually also called signal conditioning as illustrated in Figure 12.

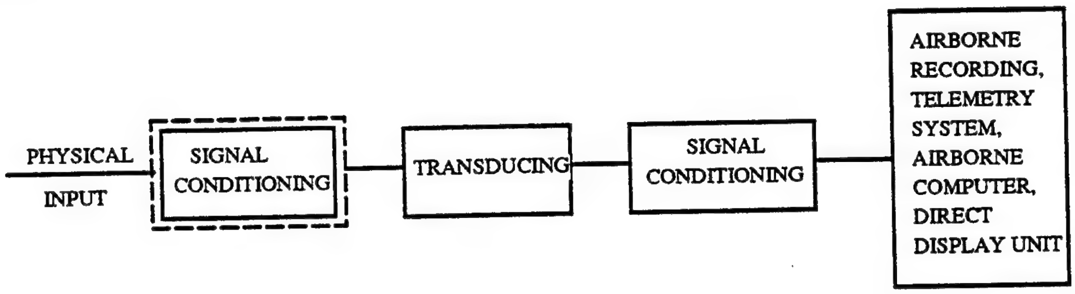


FIGURE 12. BLOCK DIAGRAM SHOWING THE FUNCTION OF SIGNAL CONDITIONING IN AN AIRBORNE FLIGHT TEST INSTRUMENTATION SYSTEM

The prime reasons for signal conditioning are that:

1) The transducers can be selected on the basis of availability or optimal transducing quality, without additional requirements on their output characteristics.

2) Transducers from the operational systems on the aircraft can also be used for flight test purposes. Conditioning circuits are used to ensure that the flight test system cannot interfere with the safe execution of the flight.

3) If the frequency range of the transducer output is too large to be handled correctly by the recording or telemetry system, the bandwidth of the signal can be reduced by eliminating frequency ranges which are of no interest for the measurements.

4) The signal can be protected against extraneous signals induced by the environment and reduce the effect on the signal by changes in the environment.

5) Amplifiers reduce the power taken from the transducer, thereby reducing the risk of changing the transducer calibration.

Signal conditioning also includes modification of the transducer output signal. As explained in the section on transducers, normally these output signals are:

- DC analog (very low frequency or quasi-static)

- AC analog (including some special types like variable impedance and synchro outputs),
- frequency and pulse rate,
- digital.

The commonly encountered signal transformations are shown in Table 2, and

CONVERSION FROM	CONVERSION TO			
	DC	AC	DIGITAL	FREQUENCY
DC	AMPLIFICATION	AMPLITUDE MODULATION	A/D CONVERSION	FREQUENCY MODULATION
AC	DEMODULATION	AMPLIFICATION	VIA DC	- - - -
IMPEDANCE	BRIDGES	BRIDGES	- - - -	FREQUENCY MODULATION
FREQUENCY	DEMODULATION	- - - -	COUNTING	
SYNCHROS	SPECIAL PURPOSE CONVERSIONS			- - - -

TABLE 2. FREQUENTLY USED SIGNAL CONDITIONING OPERATIONS

can be divided into two groups:

Linear operations, where the input and output signals are of the same type and in which the relationship between output and input can be described by a linear differential equation, and signal conversions, where the input and output signals also are linearly related but are of different types.

14.4.2 LINEAR OPERATIONS ON SIGNALS

The linear operations can be divided into four groups:

1) Amplification and attenuation

The main objective of these operations is to increase or to decrease the voltage, current, power, or impedance level of the signal. In general, the spectral distribution will also be affected slightly.

2) Filtering

The objective of filtering is to change the spectral distribution of the signal. Small changes in the desired signal components also occur unintentionally.

3) Zero shifting

This involves the addition of a constant voltage or current to the signal.

4) Compensation

The objective of this linear operation is to reduce the response to undesired variables by subtracting from the perturbed signal a similarly perturbed auxiliary signal. This technique is often used in bridge circuits and in differential amplifiers.

Amplification and attenuation:

Signal conditioning operations of amplification and attenuation usually do not significantly affect the spectral content of the desired signal. The objective of such operations is one or more of the following signal modifications:

- to change the voltage or current level in order to adapt the incoming signal to the input requirements of the recording or telemetry unit,
- to increase the power level of the measured signal,
- to match the impedance of the transducer (which may be very high) to that of the recording or telemetry system (which can be low),
- to recover a small signal level which is the difference of two higher voltage levels,
- to isolate electronic circuits from others, so that a failure in the isolated part will not affect the functioning of the remaining circuit.

Amplifiers come in many different types. A first classification includes voltage amplifiers, current amplifiers, and power amplifiers.

A second classification involves the frequency response of the amplifiers. A DC amplifier can accommodate signals with a spectral content ranging from zero to some upper cutoff frequency, which can be quite high. The passband of an AC amplifier is limited at the lower frequency side of the spectrum by a cutoff frequency above zero; it will not pass DC. AC amplifiers are used when a low frequency response is either not required or undesirable.

Amplifiers can also be classified according to the degree of electric isolation between the input and output terminals (Figure 13). Single-ended amplifiers are essentially three-terminal devices where the input and output have one terminal (ground) in common. In simple

single-ended amplifiers the common terminal is directly connected to the amplifier case and via this case to the aircraft structure (Figure 13a). In this case the measured signal will be directly influenced by ground loops (differences in potential between the points where the transducer, the amplifier and the next stage of the electronic circuit are connected to the aircraft structure). It is therefore often better to use a floating single-ended amplifier in which the common signal input and output terminal is isolated from the amplifier case (Figure 13). A signal return wire must then be added, because the signal cannot return through the aircraft structure. In modern instruments, the output terminals of the transducer and the input terminals of the next circuit are also isolated from the aircraft structure, allowing the signal return wire to be grounded to the aircraft structure at the most convenient point. In differential amplifiers the input and output sides have no common terminal (Figure 13c). Differential amplifiers function as a combination of two amplifiers with a common input ground, interconnected so that the output signal is the amplified difference between the two "hot" input terminals.

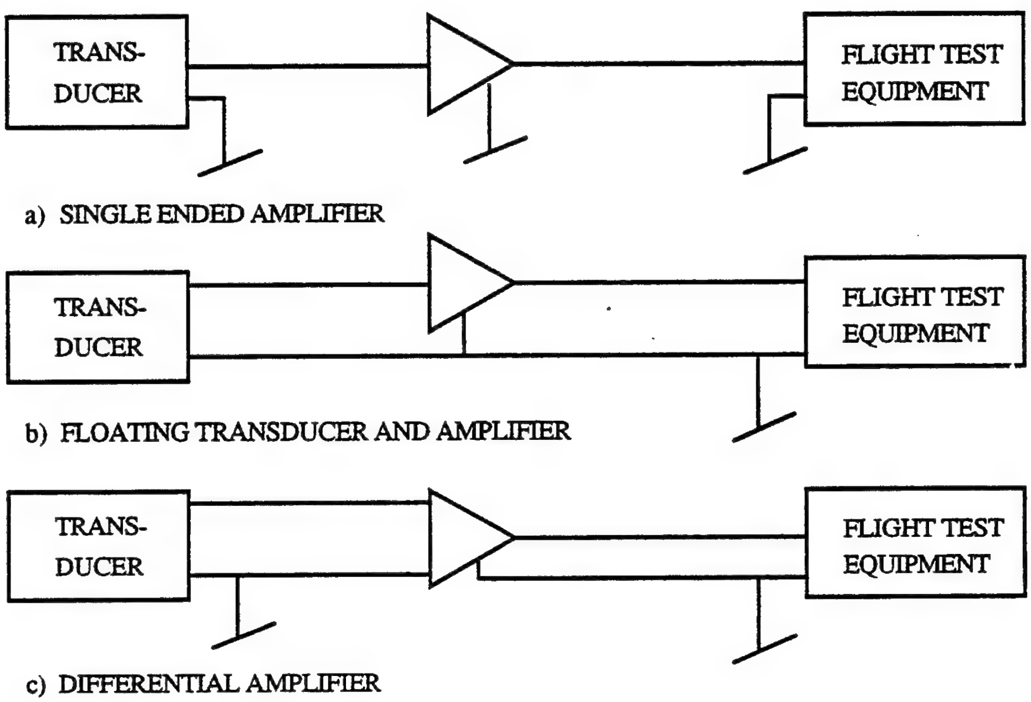


FIGURE 13. TYPES OF AMPLIFIER INPUT CIRCUITS

Attenuation:

Commonly used attenuation circuits for the reduction of high-level signals are the potentiometer and the step attenuator (Figure 14). Protective isolation can be obtained by using a series resistance (Figure 15). It should be noted attenuator circuits dissipate power, causing the signal power level to be reduced. In the case of protective attenuation, it may be necessary to provide a power amplifier in order to maintain sufficient signal power.

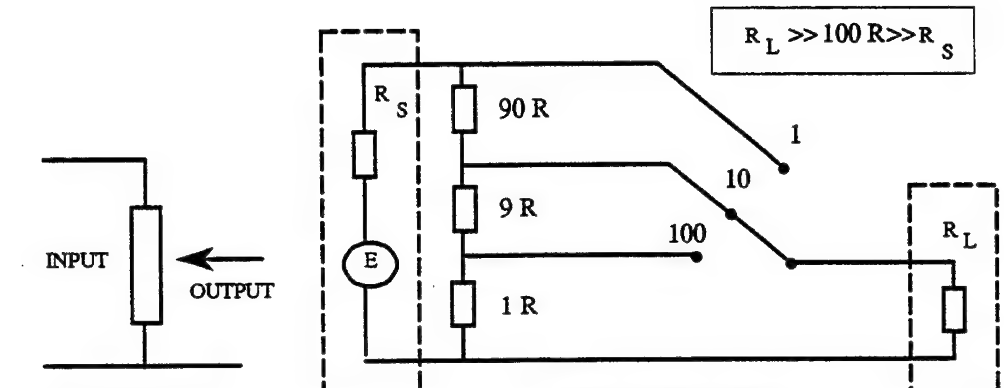


FIGURE 14. VARIABLE RESISTIVE ATTENUATION

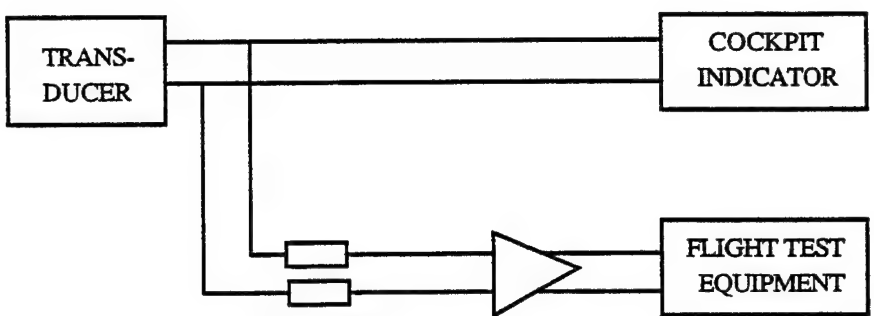


FIGURE 15. RESISTIVE ISOLATION OF THE FLIGHT TEST INSTRUMENTATION INPUT WHEN TRANSDUCERS FROM THE COCKPIT SYSTEM ARE USED

Filtering:

Filtering is done if the desired signal contains components which are of no interest to the measurement and which have frequencies which are sufficiently different from those of the signal of interest. The goal of filtering is to exclude unwanted signals without significant distortion of the measured signal. There are three main reasons for applying filtering to a measured signal:

1) To attenuate the amplitude of those signal components which are of no interest to the measurement and which may saturate transducers or other parts of the measuring circuit,

2) To filter out noise and high-frequency components of the signal which are of no interest to the measurement in order to reduce aliasing errors (sampling rate too low during commutation), and

3) To present the signal so that it can be easily interpreted.

A typical application of filtering will be explained by an example. Assume an acceleration transducer is used to measure aircraft longitudinal accelerations which are in a frequency range between 0 and 5 Hz with maximum amplitudes of ± 0.4 g. In order to obtain sufficient accuracy a feedback acceleration transducer is chosen with a range of ± 0.5 g and a frequency range from 0 to 100 Hz. The transducer will be saturated if the signal becomes larger than $\pm$ 1 g causing the output signal to become unrelated to the input signal. Besides the signal of interest there are two spurious inputs:

- a resonance of the structural member on which the transducer is mounted, with an amplitude of 1.5 g and a frequency of 30 Hz, and

- a 400 Hz signal picked up from the power supply of the aircraft by the input wires to the amplifier; the amplitude of this signal is equivalent to 0.2 g.

The spectral distribution of the input signals is shown in Figure 16. The first step must be to provide a filter to reduce the vibration input to the accelerometer to 0.5 g or less because otherwise the output of the transducer will be distorted. This must be done by means of a mechanical filter which actually reduces the 30 Hz acceleration of the transducer without distorting the frequency range between 0 and 5 Hz. Such a filter is relatively difficult to make; therefore the only alternative is to use a transducer with a linear range of ± 2 g or more, resulting in a loss in measuring accuracy. The second filter function mentioned above

becomes important if the signal must be sampled at 100 or 200 samples per second. The noise and the high frequency component must be removed, otherwise the 400 Hz signal would be aliased to near 0 Hz and would distort the low-frequency part of the spectrum which is of primary interest to the measurement. Therefore, an electric filter must be added to reduce to amplitude of the 400 Hz signal to an insignificant value.

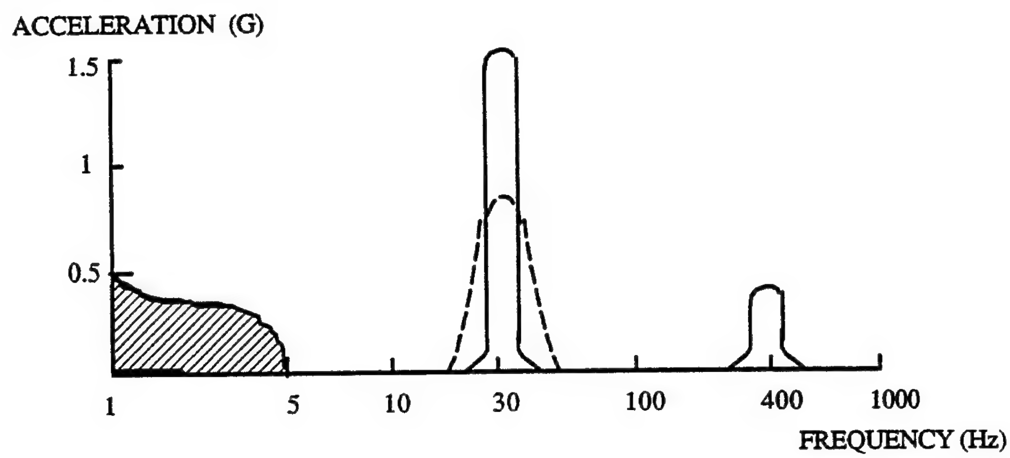


FIGURE 16. EXAMPLE OF A TRANSDUCER OUTPUT AFFECTED BY NOISE

There are several types of filters (see Figure 17). The most important filter for flight test applications is the low-pass filter which passes all frequencies below a certain frequency (cutoff frequency) and attenuates the frequencies beyond the cutoff frequency. The high-pass filter attenuates all frequencies below the cutoff frequency and passes those beyond. Band-pass filters and band-stop filters are combinations of the high and low pass filters. Filters almost always affect the phase relations in the pass band.

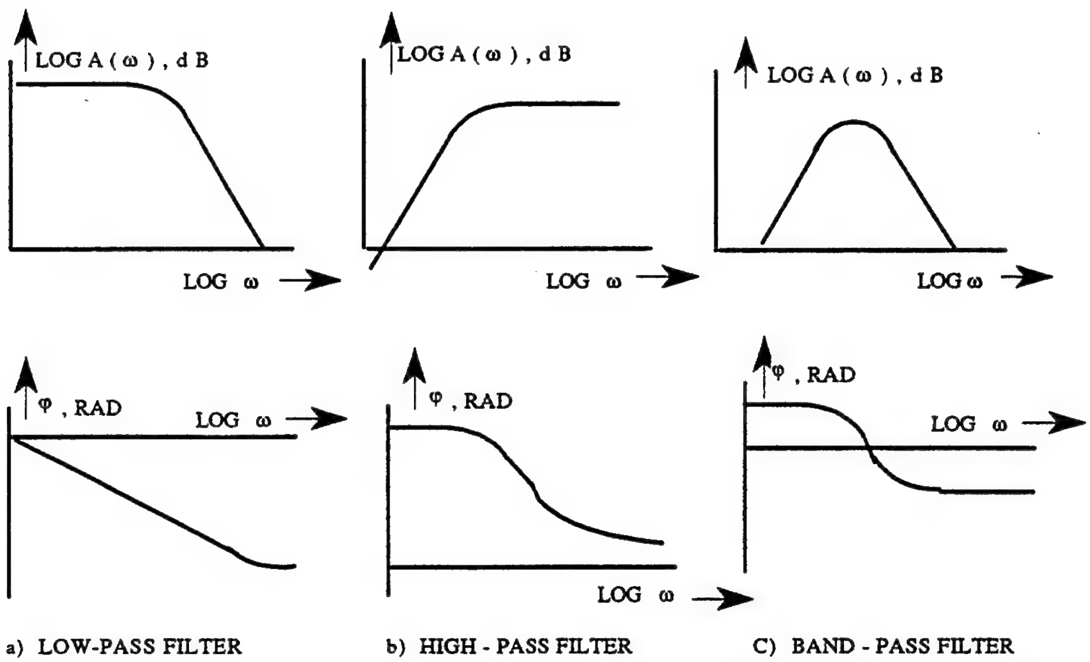


FIGURE 17. GAIN (UPPER) AND PHASE (LOWER) PLOTS OF TYPICAL FILTER TYPES

14.4.3 SIGNAL CONVERSION

General aspects:

Signal conversions are those signal conditioning operations in which the signal type is changed. The most important means of signal conversions in flight test instrumentation are:

- modulation,
- demodulation,
- analog-to-digital conversion, and
- special-purpose conversions, (e.g. synchros, resolvers).

<u>Modulation</u>

Modulation is the conversion of signal to an alternating voltage or pulse train. The most important modulation techniques are:

- amplitude modulation (AM)
- frequency modulation (FM)
- pulse amplitude modulation (PAM)

- pulse duration modulation (PDM)
- pulse code modulation (PCM)

Amplitude modulation (AM):

Amplitude modulation is the technique wherein the amplitude of a periodic wave with constant frequency (the carrier) is varied proportionally to the amplitude of the modulating signal. The information of the modulating signal is contained in the amplitude of the modulated signal. Amplitude modulation on radio frequency carriers is used in low accuracy telemetry systems. Amplitude modulation will be covered in more detail in the next section.

Frequency modulation (FM):

In frequency modulation, the modulating signal controls the instantaneous frequency of a periodic wave with constant amplitude (the carrier). Frequency modulation is used extensively in magnetic tape recording and in telemetry. It is also used when the signal must be transported via a data link that has unfavorable amplitude characteristics. This can be the case in electrically noisy environments where slip rings or rotating transformers are present or where size and weight constraints preclude circuitry of the quality necessary for high quality signal handling. Frequency modulation will also be covered in more detail in the next section.

Pulse modulation:

There are several types of analog pulse modulation methods, one of which is Pulse Amplitude Modulation (PAM). Data information is contained in the pulse amplitude level which is decoded, or demodulated to determine parameter values.

A second type of analog pulse modulation method is Pulse Duration Modulation (PDM). It reproduces a sampled signal at regular time intervals, T_r, by generating a pulse of duration T_p proportional to the magnitude of the modulation signal. The information is contained in the ratio T_p/T_r. PDM is used in conditioning functions such as multiplication and phase-to-DC converters. In PAM-PDM multipliers one input signal amplitude-modulates a periodic pulse signal, the other input signal causing PDM. Consequently, the area of the resulting pulses is proportional to the product of the input signals.

Pulse code modulation (PCM) also uses a sampled signal, but the information content of the samples is not in analog form as it is in PDM but is quantized (digitized). During each interval, T_r , a series of pulses is produced which represent the value of the input sample in coded form.

A new signal conversion technique has evolved from recent advances in opto-electronic technology through the use of light in glass fiber cables. The ease of operation and the wide bandwidth detectors, coupled with the increased reliability of glassfiber cables make the use of light as a carrier very attractive. The main advantage is that-near perfect electrical isolation can be maintained between modulator and demodulator and that the glassfiber conductor is not sensitive to electromagnetic interference.

Demodulation

A modulated signal can be restored to its original form or to an unmodulated signal of another type through demodulation. The demodulation of an amplitude modulated signal is usually done by a rectification process in which momentaneous carrier values of one polarity are inverted. A simple demodulation circuit is shown in Figure 18. The AM signal is rectified in a diode bridge circuit and then smoothed by a low-pass filter. If the range of the output signal must include both positive and negative voltages, a phase-sensitive demodulator must be used. The phase of the AM carrier signal with respect to a reference signal then determines the polarity (not the magnitude) of the demodulator output.

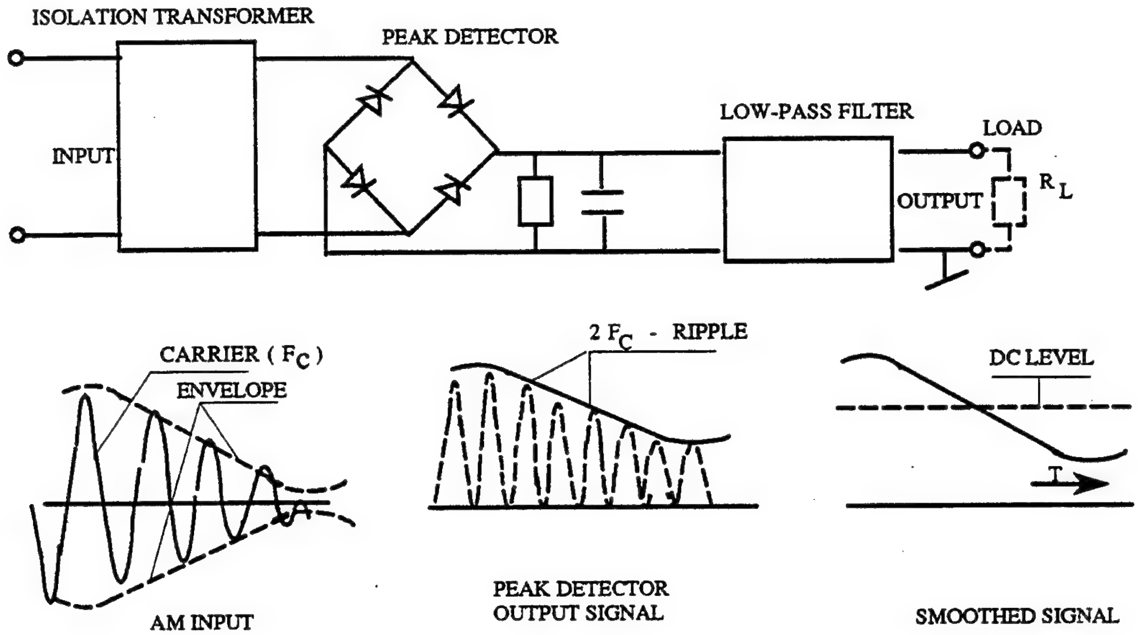


FIGURE 18. SINGLE-PHASE FULL-WAVE BRIDGE RECTIFIER APPLIED AS AN AM DEMODULATOR

Demodulation of a frequency modulated signal is called discrimination. Figure 19 shows a simple FM discriminator. The FM input is amplified, limited and differentiated, so that a series of very sharp pulses are produced. When a positive pulse enters the flip-flop circuit, the pulse starts to produce a constant-voltage output. The same pulse also starts a time generator, which resets the flip-flop after a fixed time delay which is shorter than the shortest period of the FM signal. The output of the flip-flop is therefore a train of pulses of constant height and constant width, the frequency of which is equal to the frequency of the original FM signal. After filtering, a DC signal is produced which varies linearly with the FM frequency.

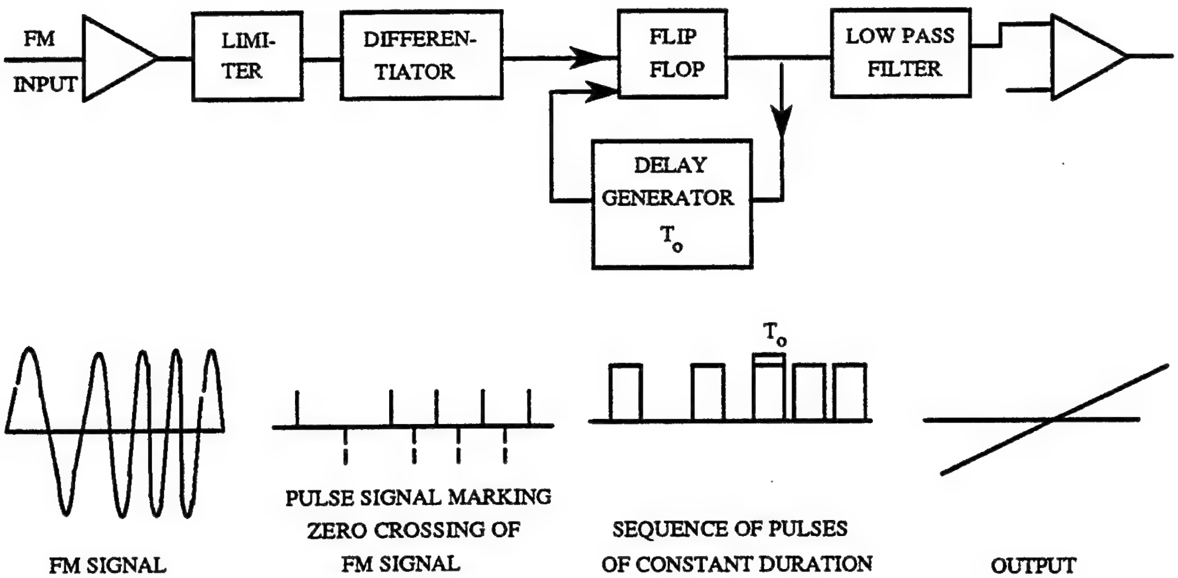


FIGURE 19. FM DISCRIMINATOR BASED ON COUNTING THE NUMBER OF ZERO CROSSINGS PER SECOND

A PDM signal is demodulated by passing it through a low-pass filter, as already described above under FM demodulation.

Demodulation of PCM signals is called digital-to-analog conversion. There are many types of D/A converters. Demodulation of a PCM signal requires that a bit synchronizer be added to the receiver circuitry. The bit synchronizer synchs on the data, identifies the sequence of bits in each number, and then converts those bits to words, analog values, and other useful outputs.

14.5 SAMPLING, COMMUTATION, AND MULTIPLEXING

14.5.1 SAMPLING

The repetitive, periodic measurement of a single signal is called sampling. Figure 20 depicts a basic sampling system which measures the transducer's conditioned signal at every time interval T. Since this signal is only a discrete sample of the signal, the accuracy of the signal representation increases as T decreases. Intuitively it is clear that a high sampling rate will yield a more accurate representation of the sampled signal. This is evident from Figure 21 in which a signal x (t) is sampled at two different rates. The higher sampling rate reduces the stair-stepping effect and improves the fidelity of the sampler output. We'll address several aspects of sampling rate later in this section.

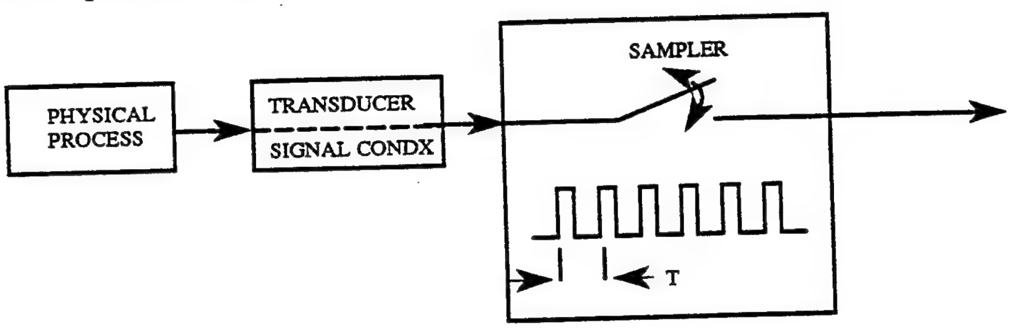


FIGURE 20. BASIC SAMPLING SYSTEM

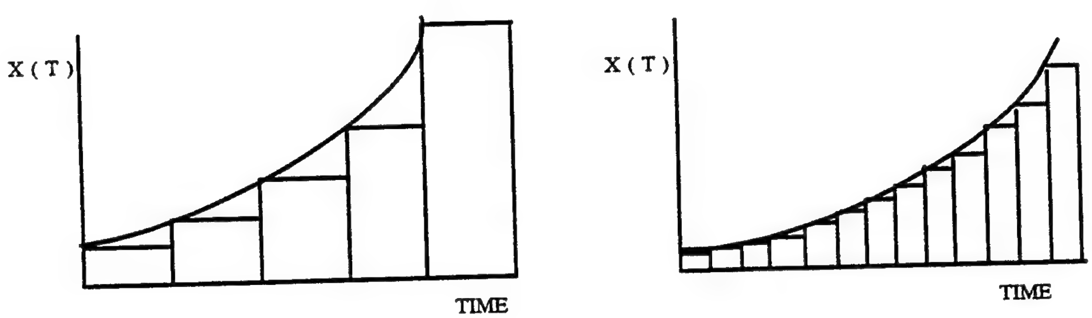


FIGURE 21. EFFECTS OF SAMPLE RATE

14.5.2 COMMUTATION

Sampling a signal leads naturally to the idea of combining the samples from several data sources through commutation. The sampling system developed in the previous section measured the input signal once every T seconds. Commutation allows the sequential measurement of several signals every T seconds. Figure 22 illustrates this concept.

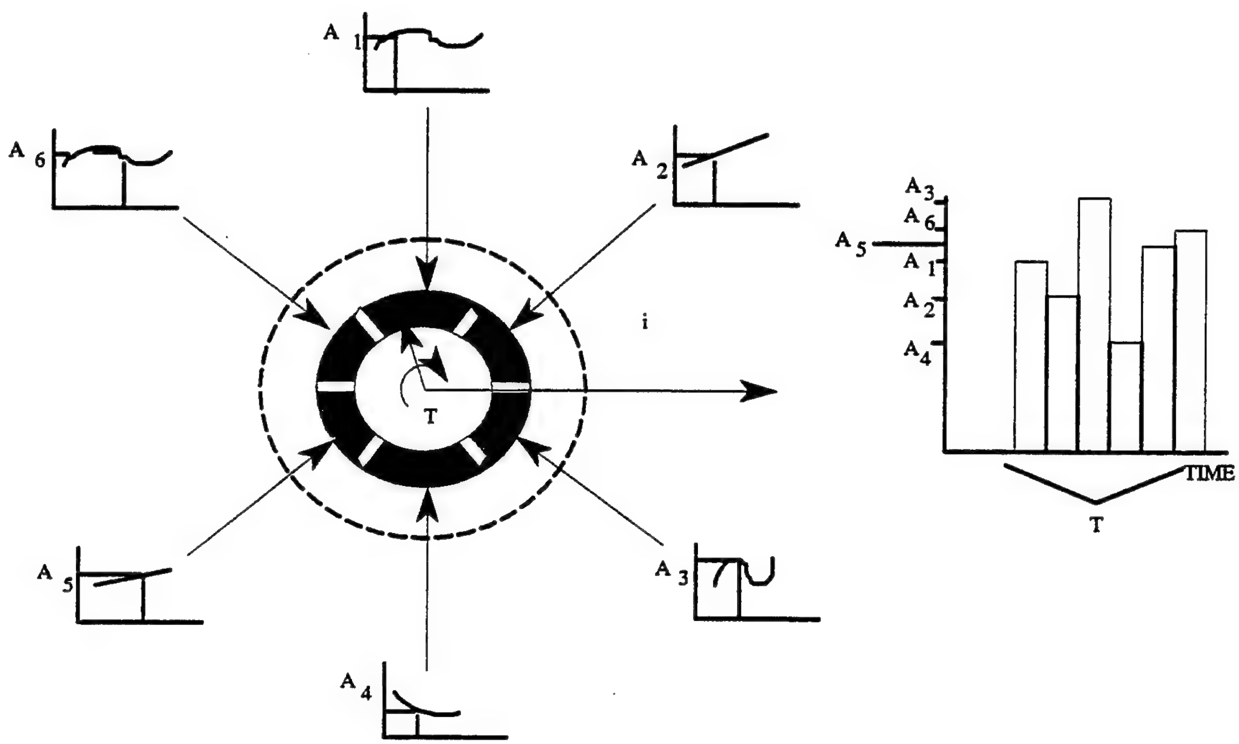


FIGURE 22. THE COMMUTATION PRINCIPLE

The term commutation refers to the sequential sampling, on a repetitive basis, of multiple data sources all merged onto a single channel for subsequent signal processing, transmission, and/or recording. Commutation is another name for time-division multiplexing. Figure 22 shows the commutation principle for six signals. Note that the multiplexed signal consists only of a series of pulses, the amplitudes of which are determined by the amplitudes of the original signals at the instant they are sampled. A basic commutation/decommutation system, is depicted in Figure 23.

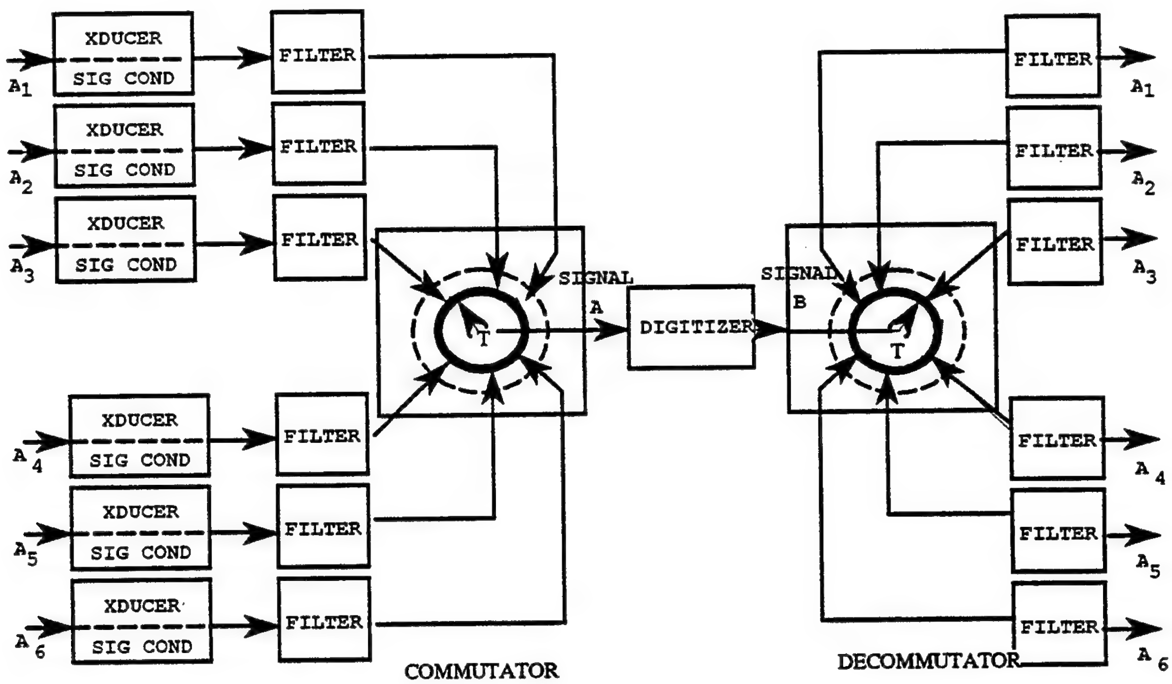


FIGURE 23. A BASIC COMMUTATION SYSTEM

Signal A in Figure 23 consists of a complicated series of pulses. There are 6 pulses every T seconds, and each pulse corresponds to the instantaneous amplitude of one of the input signals. Notice that signal A can contain negative as well as positive value pulses.

In most applications, signal A modulates another signal, called a carrier with the resulting signal being compatible with the transmission or recording channel. If signal A is used to directly amplitude modulate a carrier, the process is called Pulse Amplitude Modulation (PAM). This method is used in some telemetry and recording systems.

Another common technique is to first code the amplitude of each pulse in signal A and use the code to modulate a carrier. This is called Pulse Code Modulation, PCM. Normally a binary coding scheme is used to code the amplitude of each pulse. Figure 24 shows the sampling signal x_s (t), signal A, and signal B, where signal B is a 4-bit binary representation of the individual pulses of signal A.

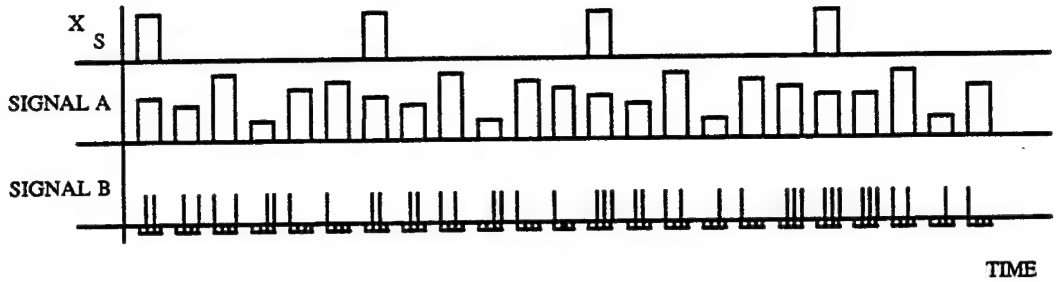


FIGURE 24. COMPARISON OF THREE SIGNALS IN A COMMUTATION SYSTEM

Before we investigate modulation and multiplexing, there are two specialized types of commutation: supercommutation and subcommutation.

Supercommutation increases the sampling frequency of a channel by sampling the data signal more than once per frame. This can be done by paralleling some channels of the commutator. Obviously, the number of data channels decreases as the sampling frequency increases. The example in Figure 25 shows the substitution of 24 channels with a sampling frequency of f_C by 10 channels with different sampling frequencies ranging from f_C to 4 f_C.

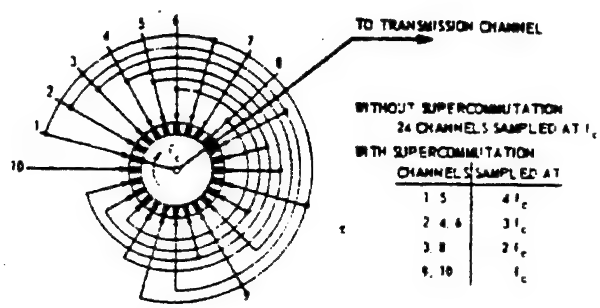


FIGURE 25. SUPERCOMMUTATION

Subcommutation means the decrease of the channel sampling frequency by substituting one channel of the main frame sampling frequency f_C with n channels of a sub-frame using a sampling frequency f_C/n. The example in Figure 26 shows the increase of the number of channels from 6 channels using a sampling frequency f_C to 16 channels using sampling

frequencies ranging from f_c down to $f_c/36$ by means of two subcommutation processes in cascade. Subcommutation is used in a similar way in commutators using relays or electronic switches.

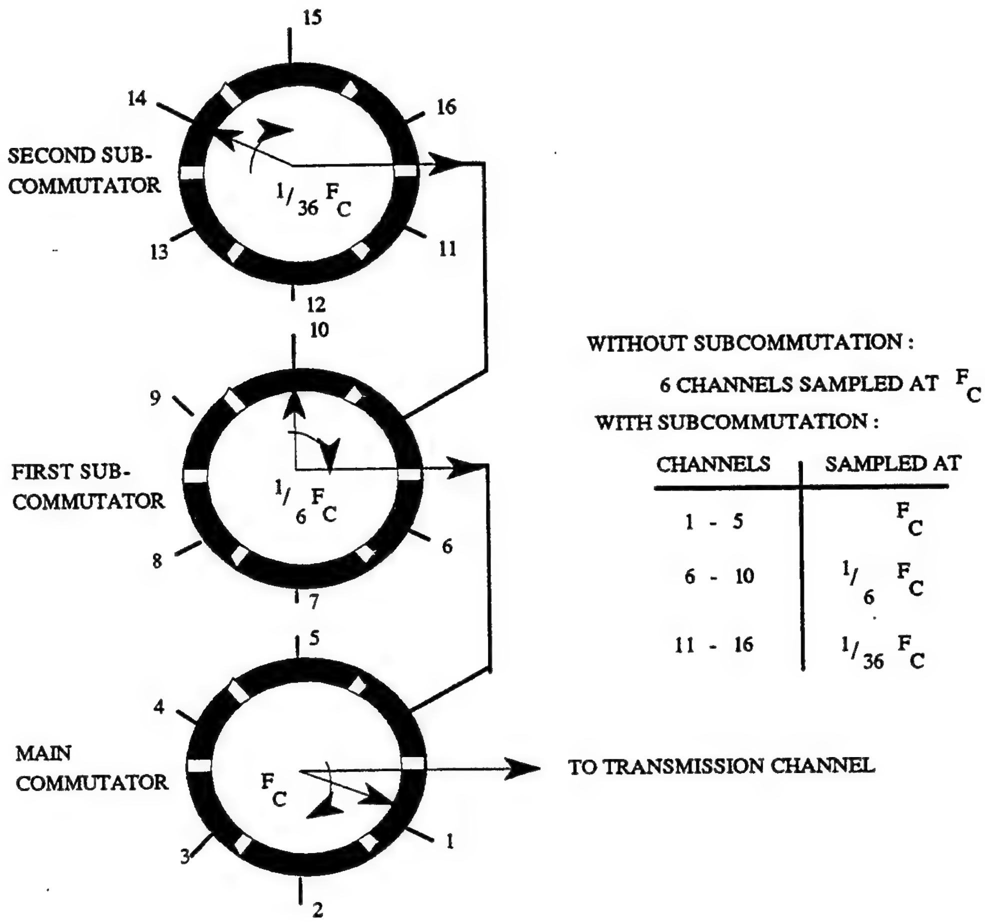


FIGURE 26. SUBCOMMUTATION

14.5.3 MODULATION AND MULTIPLEXING

Description of the basic methods:

In general, the purpose of modulation is to match a signal to a specific transmission channel. The purpose of multiplexing is to transmit two or more signals over the same data channel without cross talk. In practice the signal is often subjected to both processes. Therefore, modulation and multiplexing are treated in the same discussion.

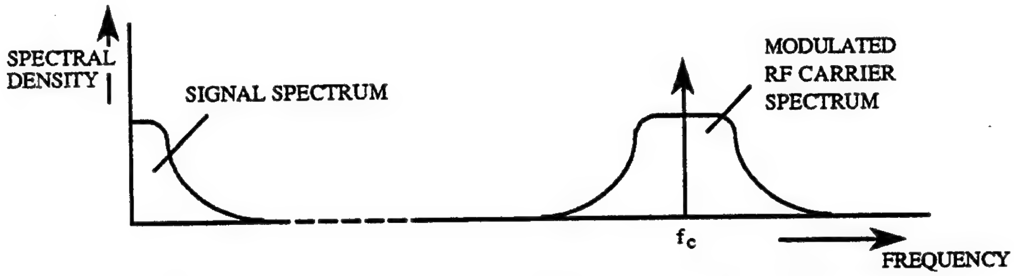
Four different objectives of modulation are illustrated by Figure 27. These are:

a) Shifting the signal spectrum to the frequency band of the transmission channel (e.g. shifting the voice spectrum by amplitude modulation to the assigned radio-frequency voice communication channel),

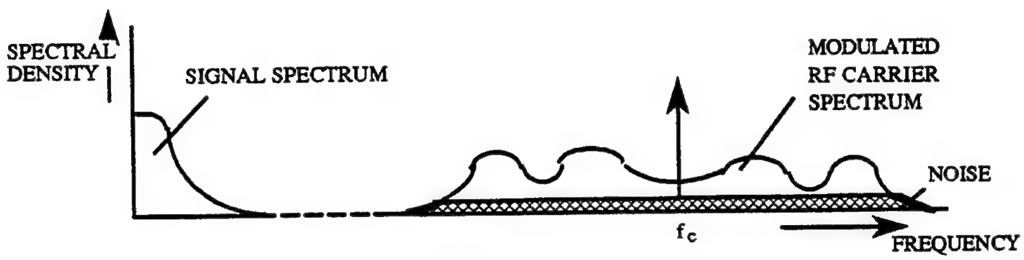
b) Widening the shifted signal spectrum in order to get better protection against channel noise (e.g. by using frequency modulation),

c) Grouping a set of signals by means of modulated subcarriers or pulses and then modulating the rf-carrier by this composite signal (frequency-division multiplexing or time-division multiplexing, respectively),

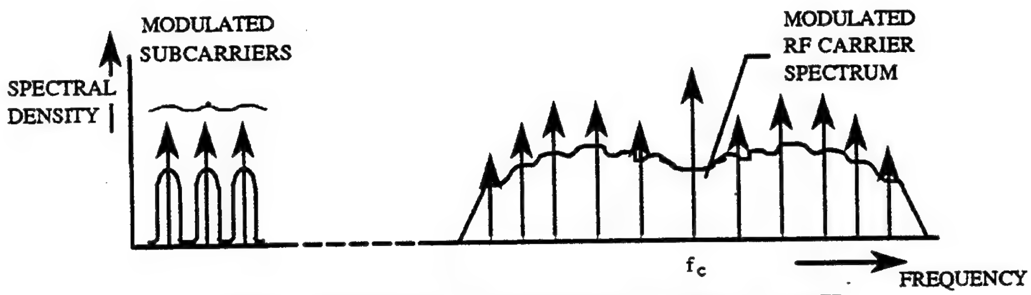
d) Matching a signal to a specific channel, (e.g. to a tape recorder direct channel).



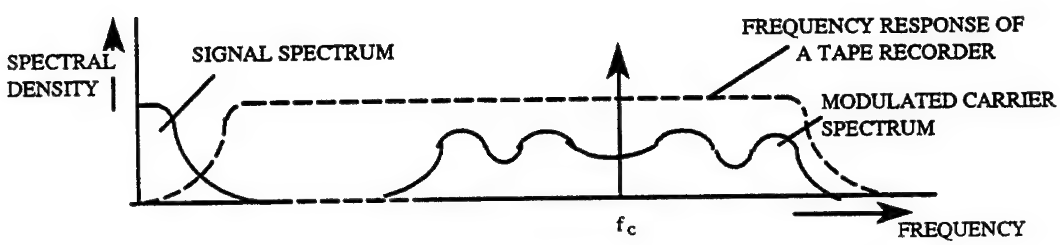
A. SHIFTING THE SIGNAL SPECTRUM TO THE TRANSMISSION FREQUENCY BAND



B. WIDENING THE SHIFTED SIGNAL SPECTRUM



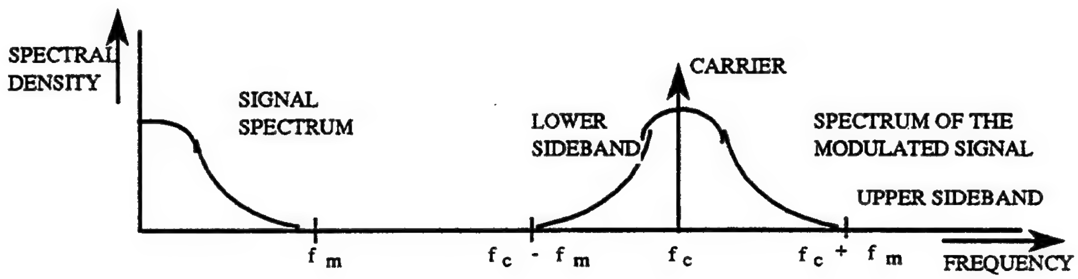
C. MODULATING SEVERAL SUBCARRIERS ON ONE RF CARRIER
(FREQUENCY - DIVISION MULTIPLEXING)



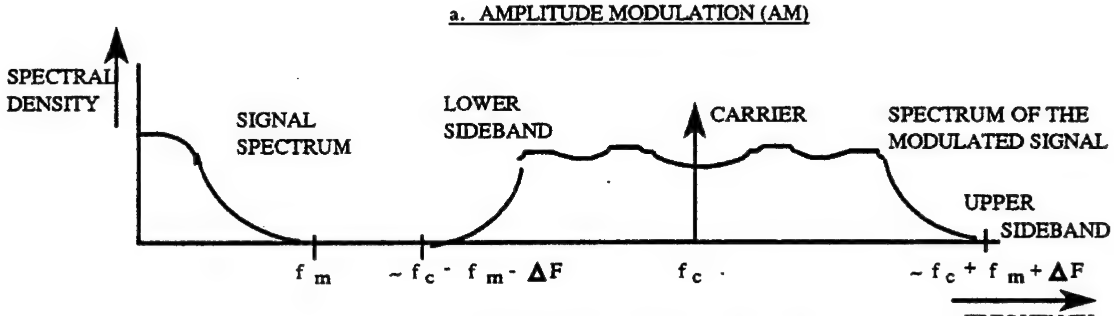
D. MATCHING THE SIGNAL TO THE RESPONSE CHARACTERISTICS OF, E.G., A TAPE RECORDER

FIGURE 27. OBJECTIVES OF MODULATION

The usual modulation methods are shown in Figures 28 and 29. We have to distinguish between the continuous modulation methods and the pulse modulation methods. In the first case, the parameters of a sinusoidal carrier (amplitude, frequency and phase) are controlled by the signal voltage. The modulated carrier can be described best in the frequency domain by its spectrum (see Figure 28). For the pulse modulation methods, the parameters of a pulse carrier (amplitude, duration) are controlled by the signal voltage (see Figure 29). In this case the modulated carrier can be displayed more clearly in the time domain by its time function.



a. AMPLITUDE MODULATION (AM)



b. FREQUENCY MODULATION (FM)

FIGURE 28. CONTINUOUS MODULATION METHODS

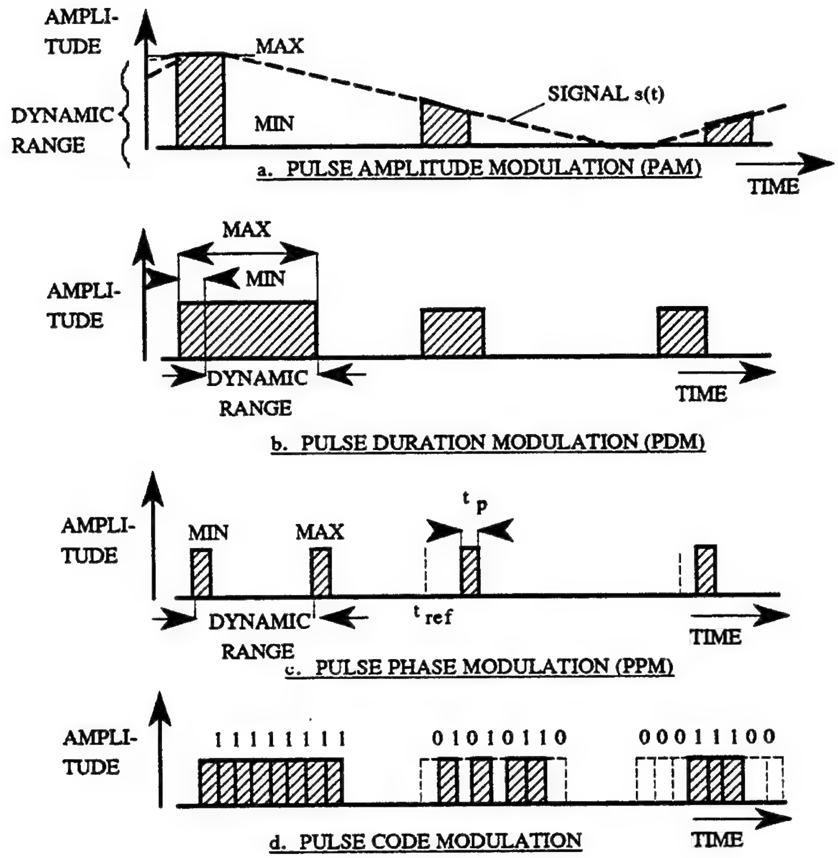


FIGURE 29. PULSE MODULATION METHODS

The time function of the modulated carrier for amplitude modulation (AM) is:

$$u(t)_{AM} = U_C \cdot \{ 1 + m*s(t) \} \cdot \cos(w_C \cdot t)$$

with the carrier wave $U_C \cdot \cos(w_C \cdot t)$. The normalized signal time function s(t) is bounded by ± 1. The range of modulation factor m usually is $m \leq 1$. The spectrum of the modulated wave consists of one line at the carrier frequency w_C and an upper and lower sideband. The upper sideband is obtained by shifting the signal spectrum by w_C along the w-axis. The lower sideband is the image of the upper sideband, symmetrical to w_C. Therefore, the bandwidth of the AM spectrum is twice the bandwidth of the original signal spectrum.

For a deeper understanding of modulation it may be worth mentioning that a close connection exists with the sampling theorem. We assume a signal spectrum with an upper

frequency limit f_m. When the carrier frequency f_0 is less than 2 f_m, there will be frequencies at which the unmodulated and the modulated signals overlap. This will cause aliasing errors when the signal is demodulated.

Frequency modulation (FM) (Figure 28b) is a wideband modulation method which makes use of an extended bandwidth in order to improve the signal-to-noise ratio. Because of the relatively simple hardware, FM is of great importance for flight testing. In FM the frequency of the carrier wave is modulated in the following way

$$f_{FM} = f_c + \Delta F * s(t)$$

where f_c is the frequency of the modulated carrier, ΔF is the frequency deviation and s(t) is the normalized signal. It can be shown that the increase of the signal-to-noise ratio is proportional to the ratio M, where

$$M = \frac{\Delta F}{f_m}$$

M is the so called modulation index of f_m, the highest frequency component of the signal spectrum. Unfortunately, the bandwidth of the FM-spectrum increases as a linear function of ΔF, thus limiting the obtainable gain because of the general restrictions on available bandwidth. For f_m subcarriers, modulation indices of 5 are used in practical applications for flight testing.

A special case of FM is the phase modulation (PM). This is accomplished by letting the signal s(t) control the carrier phase instead of the carrier frequency. Its special feature is a preemphasis which increases the amplitude of the signal spectrum linearly with frequency.

In pulse amplitude modulation (PAM) (Figure 29) the signal s(t) is sampled at discrete points in time.

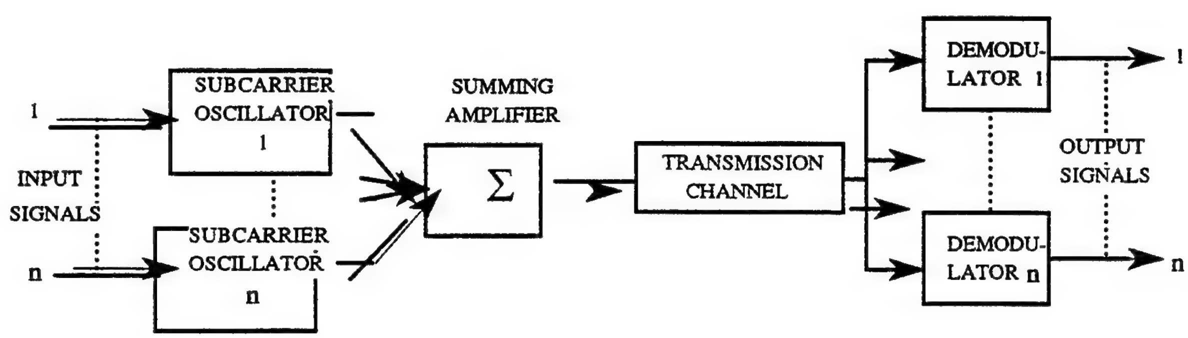
Pulse duration modulation (PDM) (Figure 29b) is obtained by converting the amplitude of the PAM samples into a pulse duration. Thus a train of pulses with variable width is generated and the dynamic range of the signal is transformed from the amplitude domain to the time domain. The minimum value of the signal s(t) corresponds to the shortest pulse duration and the maximum value of s(t) corresponds to the longest pulse duration. The amplitude of the PDM pulse train remains constant.

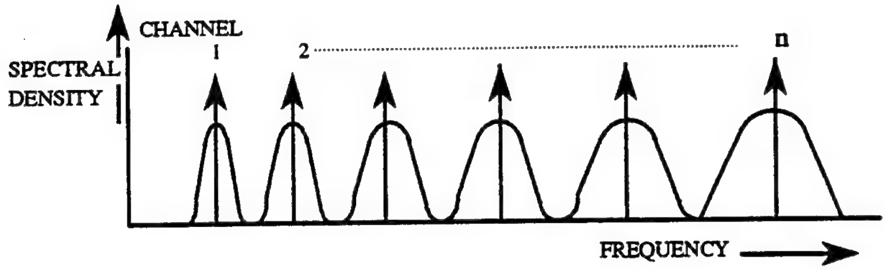
For the sake of completeness, pulse position modulation or pulse phase modulation (PPM) is also displayed in Figure 29c, though it is not a standard modulation method in telemetry. In these methods the relative position of a pulse is controlled by the signal. A time reference is required for demodulation.

Due to the great technological progress in integrated circuits, the use of pulse code modulation (PCM) has become important during the last few years. In this method the PAM samples are coded in a "word" of N pulses, using only the levels 0 and 1. Since PCM is a digital method, any required accuracy can be obtained by the proper choice of the word length. PCM also makes excellent use of the law of exchangeability between signal-to-noise ratio and bandwidth.

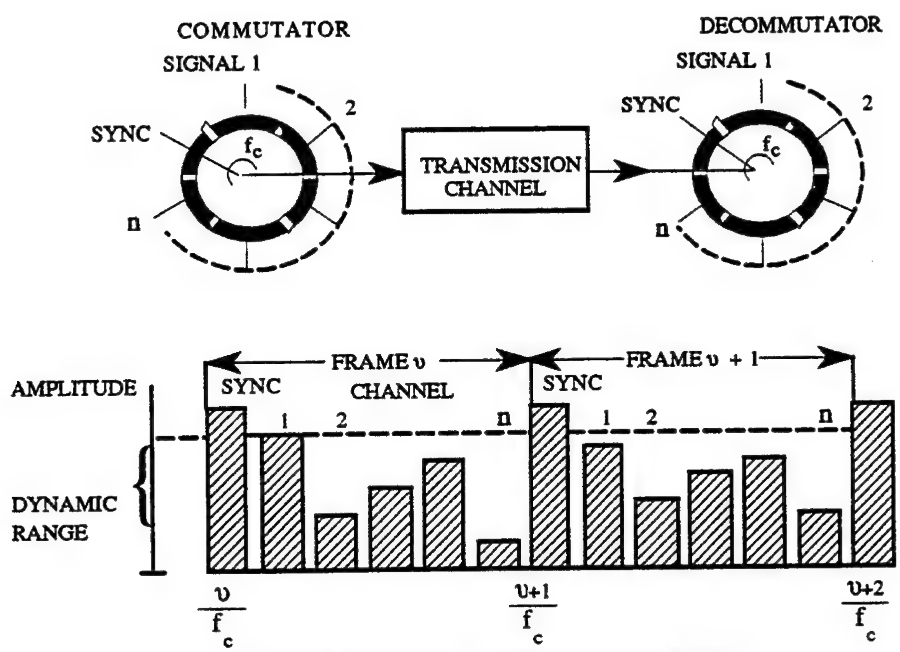
PCM is widely used in time domain multiplexing systems. Serial format PCM can be derived from a PAM signal by an analog-to-digital converter with serial outputs. The clock frequency for the A/D converter must be N-times the PAM sampling frequency. This obviously shows the increase in bandwidth. N, the number of bits for each sample, is determined by the required amplitude resolution. PCM is less sensitive to errors due to noise because only two levels of the signal are possible. There are various formats for encoding the two levels 0 and 1. In Figure 29c the "non return to zero-change (NRZ-C)" format has been used.

Figure 30 illustrates the two multiplexing methods used in practice: frequency-division multiplexing and time-division multiplexing.





a. PRINCIPLE OF FREQUENCY - DIVISION MULTIPLEXING



b. PRINCIPLE OF TIME - DIVISION MULTIPLEXING

FIGURE 30. METHODS OF MULTIPLEXING

The method of frequency-division multiplexing (Figure 30a) is generally used with continuous modulation methods, such as AM, DSB, SSB or FM. Each data signal modulates a subcarrier with a different frequency. By proper selection of the subcarrier frequencies, overlapping of the modulation spectra can be avoided. At a receiver end of the transmission link the individual subcarriers are separated by band-pass filters. The data signals are recovered by demodulation of the subcarriers.

Time-division multiplexing is generally used with pulse modulation methods, such as PAM, PDM, PPM and PCM. Figure 30b is based on PAM. A commutator, e.g. a rotary switch, samples n different data signals with the same sampling frequency f_C , but at consecutive points in time. Thus, a train of non-overlapping pulses is generated which may be decommutated by a synchronously running switch at the receiver end of the transmission channel. In order to obtain the required synchronism, a synchronization signal must be inserted in the pulse train, which can be detected by the decommutator and can be used for synchronizing the position of the switch. Therefore, the synchronization signal usually is given a value outside the dynamic range of data signals.

14.5.4 BANDWIDTH

The term bandwidth is used to describe the range of frequencies in which the information (data) is carried. Bandwidth is a critical performance specification. Any component (in a signal processing system) which is not capable of handling the bandwidth of desired signals will act like a filter, thereby reducing the amount and accuracy of the data.

For example, the bandwidth of channels carrying discrete information does not need to be large because of the limited information being carried (either on or off, or open/closed). Other channels that carry "fine-divisioned" data, such as temperature, pressure, or voltages, require larger bandwidths in order to discriminate the data values to the required accuracy.

14.5.5 MINIMUM SAMPLING RATE

Figure 21 illustrates the intuitive observation that the sampling rate has an important effect on the fidelity of the signal. When the sampling rate of a signal during commutation is too low, this undersampling can lead to a phenomenon called aliasing. Figure 31 depicts the apparent reconstructed signal as opposed to the actual sampled signal. Figure 32 illustrates the reconstruction of the signal using a higher sampling rate.

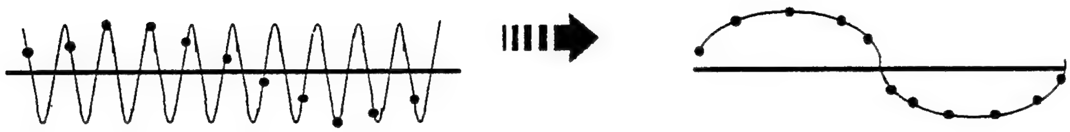


FIGURE 31. ALISSING DUE TO UNDERSAMPLING

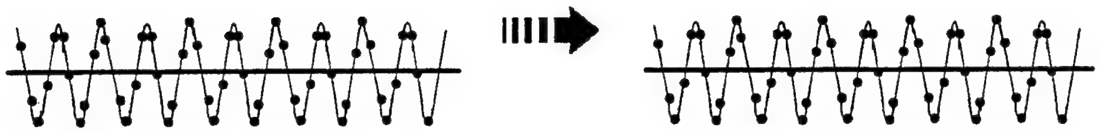


FIGURE 32. PROPER SAMPLING RATE

Although the theoretical minimum sampling rate is twice the highest frequency component of the sampled signal, in practice it is usually taken to be 4 to 5 times this component. This is due largely to limits and trade-offs made in the design and operation of the filters used in the sampling circuit.

14.6 AIRBORNE DATA RECORDING

14.6.1 INTRODUCTION

Onboard recording is the most generally used method of data storage in flight testing. Even when telemetry is used, the same data are often also recorded onboard the aircraft to ensure that they will not be lost if the telemetry link should fail.

The earliest and simplest method of onboard recording was the use of a knee pad and pencil by the pilot or observer who wrote down his readings of the cockpit instruments. In the last few decades there has been a rapid development of the first photographic methods and later tape-recording methods. This development has shown a double trend:

- a specialization between direct-indication instruments (for the flight crew) and measuring devices specially mounted for flight test purposes and
- a continuous increase in system performance evidences by the number of recorded channels, bandwidth of each channel, accuracy, ease of processing, etc.

In the course of this development process the following recording methods have come into general use for flight testing.

- photo panel recorders (from about 1930)

- continuous-trace recorders (from about 1940)
- analog magnetic-tape recorders (from about 1950)
- digital magnetic-tape recorders (from about 1960)
- video recorders (from about 1970)

Despite their differences in age, none of these methods are yet obsolete. Although the more modern methods are generally preferred for large-scale test programs, the older methods can often be used very cost-effectively for tests where high performance is not a prime requirement, especially if there is no direct access to a complex data processing station. In this chapter the analog, digital, and video methods will be discussed.

Other recording methods are used under special circumstances. Photo or cine cameras are used for making pictures of tuft or ice-accretion patterns on wings, for measuring dynamic movements of the wing or tail with respect to the central fuselage, and for many other purposes.

14.6.2 EXAMPLE OF AIRBORNE DATA COLLECTION SYSTEM

The Modular Data System (MDS) serves as an example of a redundant data recording system. The redundancy in data recording becomes more important as the number and expense of flight test assets increase. It is worth the extra cost of using a backup recording system to ensure that complex flight tests have to be accomplished only once rather than repeat them due to a failure in the data recording system. The MDS utilizes a combination of analog and digital onboard recording systems to ensure successful test completion the <u>first</u> time. A schematic of the MDS is shown in figure 33.

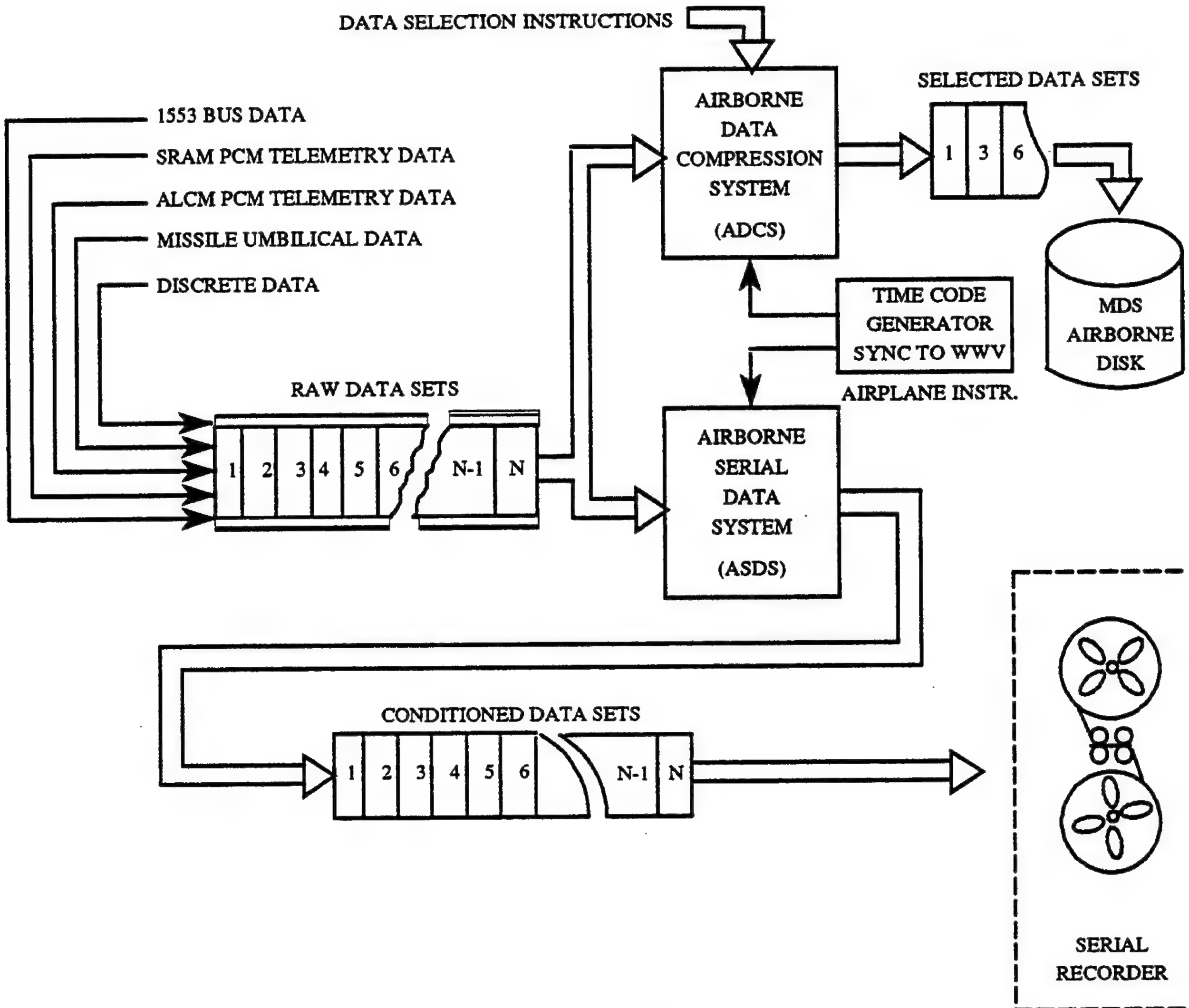


FIGURE 33. MODULAR DATA AIRBORNE SYSTEMS

The analog portion of the MDS is called the Airborne Serial Data System (ASDS), which receives serial data from the MIL-STD 1553 data bus , weapon umbilicals, and discrete data sources. The term "serial" in the analog data system refers to a stream of data that arrives at the ASDS as a sequence of raw data sets. This stream of data can represent the sequence of data arriving from a multitude of transducer signal conditions. The ASDS then "conditions" these data for recording onto a serial recorder.

For example, consider the data from three transducers: a static pressure sensor for altitude, a pilot/static sensor for airspeed, and an angle of attack (AOA) sensor. The data

signals from each of these are conditioned so that they are all compatible with the input to the ASDS in the PCM format, as shown in figure 34, and the signals are commutated (sampled in sequence,

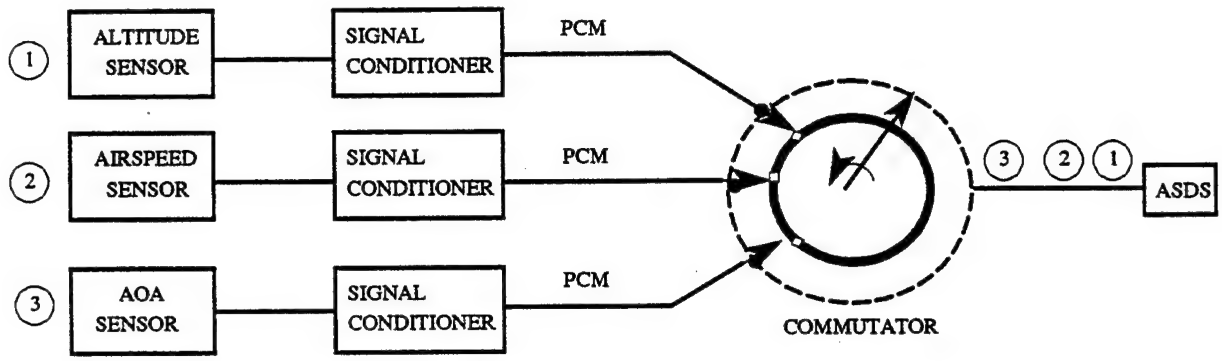


FIGURE 34. ASDS INPUTS

or time-division multiplexed to the ASDS). The output of the commutator is a series (or stream) of "bit words" that represent the sampled altitude, airspeed, and AOA signals in that sequence. While the 1553 bus data are represented by 16-bit words, Figure 35 would depict a series of data input to the ASDS as 4-bit words.

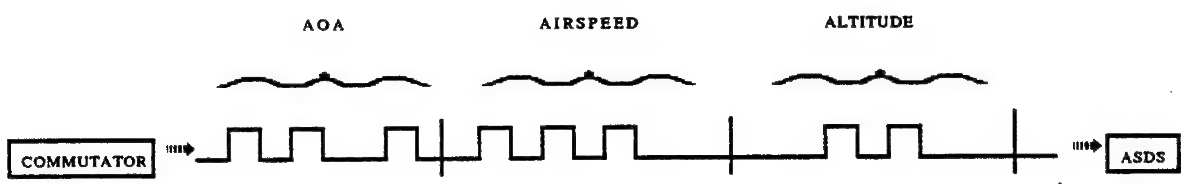


FIGURE 35. PCM DATA STREAM

These data words can be and are directly entered onto a recording tape, but a decommutator is still required to sort out which words belong to the altitude sensor, which belong to the airspeed, and so forth. The ASDS does this decommutation and more. Prior to directing the PCM stream onto a serial recorder, the ASDS inserts: 1) synch pulses to ensure that each data word is identified in its proper sequence, 2) timing pulses so that proper timing identifications can be made, and 3) a track number for the recorder. Additionally, if no data are coming from transducers, the ASDS inserts "filler words" that provide an ongoing

recording system check and "funny words" that identify whether the words that follow are filler words or real data.

This happens rather quickly-the 1553 serial bit rate is about one million bits per second (or 1 megabit/sec). However, the serial recorders that are used can usually record only 500 kilobits per second, or about half the rate of the incoming stream of data. To solve this problem, data <u>tracks</u> are used.

It was mentioned above that a track number is assigned by the ASDS, meaning that the data is directed to a particular spot on the recording tape. Figure 36 illustrates this principle in which all the altitude data is directed to track 9, while assigned data goes to track 11 and AOA data is recorded on track 16.

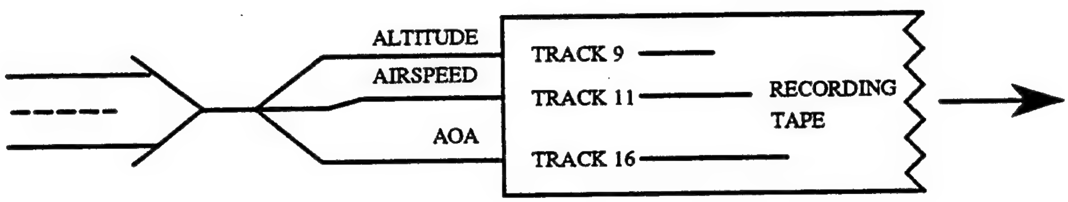


FIGURE 36. SERIAL DATA RECORDING

This separation of the data (after decommutation) into tracks allows the simultaneous recording of multiple data sensor signals at a rate compatible with the recorder hardware. When the recorder tape (in the MDS, it contains 28 tracks) is full, it is rewound, duplicated, and checked for valid data. The data can be extracted, processed, and analyzed. The tracks of interest during the time periods of interest can be selected from the large amounts of recorded data for printout onto paper or selected for viewing on computer screens.

What happens if the ASDS processor crashes? Recall that the raw data can be (and usually are) recorded on backup serial recorders prior to being processed by the ASDS, space and money permitting. This backup process provides additional redundancy to ensure complete data collection, since these raw data can be run through an ASDS processor in the ground station and the ASDS can't tell the difference. Why, then, even carry the ASDS and serial recorder in the aircraft?

In multiplace aircraft, the ASDS can allow real time data review for the crew from each of the input transducers to ensure:

1. compliance with test conditions, and

2. validity of data being recorded.

14.6.3 DIGITAL RECORDING SYSTEMS

The analog system described above processed the data streams into multiple analog tracks composed of the PCM formats. The digital systems use airborne disks as a recording medium for processed outputs of the same data stream coming in from the aircraft, weapon umbilicals, and discrete data sources. One such digital system , the Airborne Data Compression System (ADCS) takes the incoming raw data stream and makes the decision whether or not to record the data digitally, based on criteria input by the user prior to the flight. Figure 37 illustrates the ADCS schematically. Basically, all the data from the source transducers go into the digital system, but only selected data get recorded.

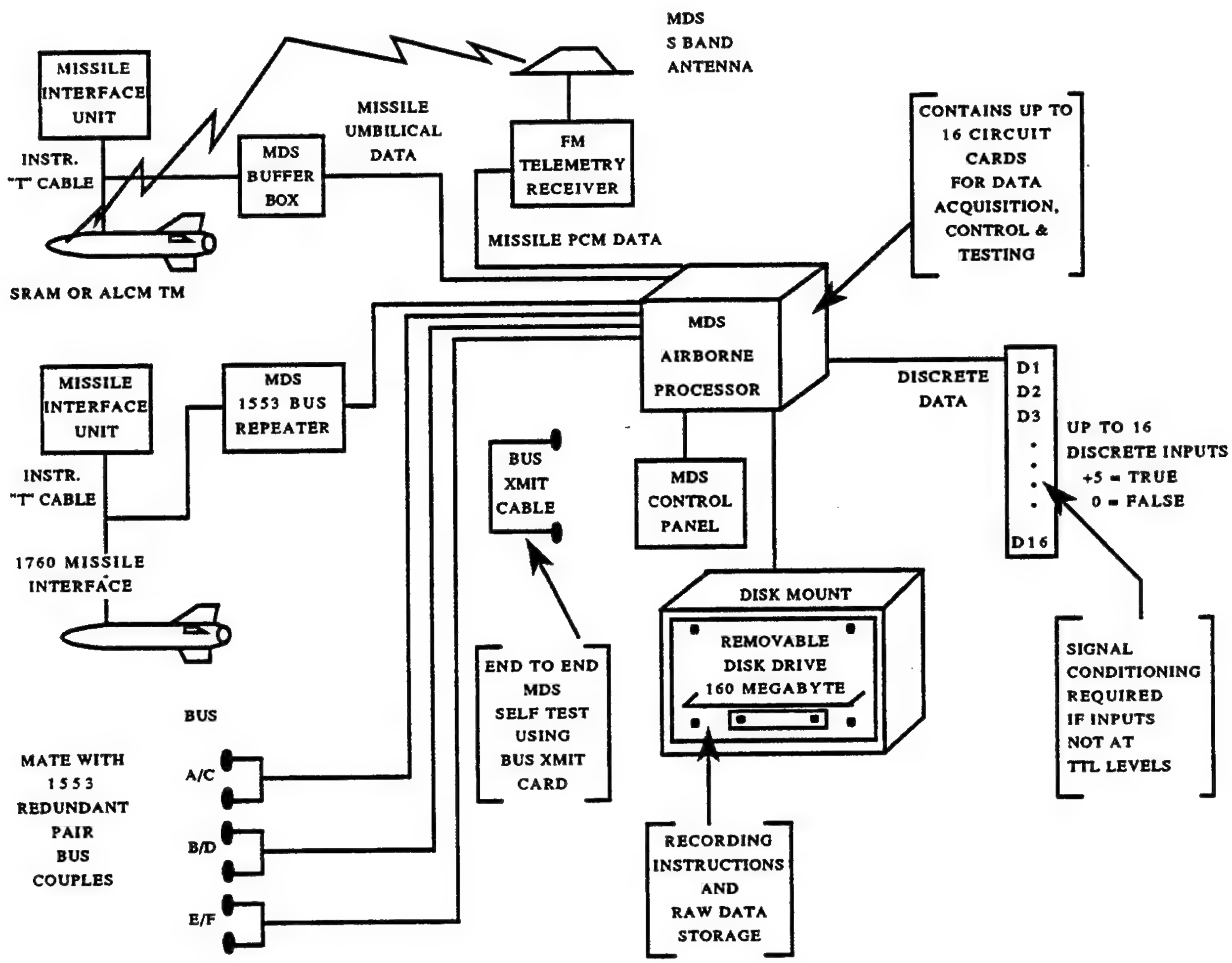


FIGURE 37. BASIC AIRBORNE DATA COMPRESSION SYSTEM (ADCS)

In order for the ADCS to decide which data to select, it relies upon a "working catalog" that the test engineer and the data engineer develop together on the ground prior to flight. This working catalog selects all altitudes within 200 feet of 35,000 feet pressure altitude, for example, or all airspeeds above 450 knots, for recording. Depending on the test points, the catalog can isolate the conditions of interest, exceedances, or data within specified tolerances. When used in conjunction with the ASDS, the catalog provides redundant data recording of specified conditions. The working catalog is brought to the aircraft where it is entered into the ADCS processor, which in turn builds an "edit table" from the working catalog. This edit table functions like a series of notch filters which compare the incoming

data source, data value, and data occurrence with the table to determine whether the meet the "recording criteria". If the data meet the recording criteria, then they are transferred to the disk. If not, they are ignored. The transfer to disk (one of two available) is made via two buffers , each of which fills with data prior to dumping the disk. As one buffer transfers, the other fills.

Obviously the size of the disk(s) determines the amount of data able to be stored during flight test. On the ADCS, two disks of 160 megabytes each are used. As the full buffer is transferred to the active disk (while the other buffer fills), the ADCS checks the remaining space available on the active disk. If this space is insufficient to receive the next buffer, the ADCS transfers the next buffer to the second disk. Using this method no data will be overwritten.

The postflight transfer of data from disk to a 9-track tape illustrates the difference between serial and parallel recording. The process of serial recording was described in the preceding analog section. Parallel recording uses the simultaneous recording of nine bits across the width of the magnetic recording tape (Figure 38). The nine bits (hence, the 9-track tape) contain the 8-bit data word and one bit for parity. Parity is used to distinguish the proper data read during playback. Thus, the parallel data recording uses tracks, like serial data, but does not assign specific data to each track, but assigns the bits comprising the data word across the width of the tape.

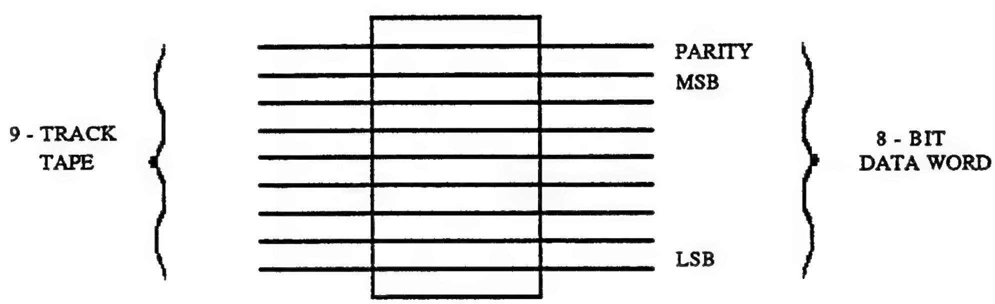


FIGURE 38. PARALLEL RECORDING

14.6.4 VIDEO RECORDING SYSTEM

With the common usage of consumer/commercial video recording equipment, a flight test video recording system should be familiar to most students. Basically, this onboard

system records the electronic video signals just upstream of where the information is normally displayed to the crew member. As an example, if the pilot's heads-up display (HUD) or the radar navigator's multifunction display (MFD) contain the data required for the testing, then an instrumentation video recorder is inserted into the basic aircraft system such that all data are recorded for postflight playback and analysis as well as being displayed during the flight. Radio transmissions and interphone communications are also usually recorded via the video recording system.

Photographic data are also collected for various types of tests in addition to video recording of displayed parameters. Examples of the use of photographic data include:

- store separations (from externally mounted cameras on the test aircraft as well as from photo chase photographers)

- ice accretion (from externally mounted cameras focused on a colored, mounted depth gauge or form the water spray tanker)

- flow characteristics displayed on a tuft pattern taped to the aircraft structure or on a dye pattern (from internally or externally mounted cameras or from photo chase)

- weapons bay door operations (from internally mounted cameras and lights).

For stores separations, both in-flight and ground box drops, high speed cameras and film (e.g., 100 to 200 frames per second) are used to slow the movement down for proper analysis. Higher speed film transport limits the run time available and great care must be taken to start the cameras just prior to the event to ensure coverage of the separation itself. More than one test has run out of film just prior to the critical event due to confusion and misunderstanding of the cue to start cameras.

A third segment of a video/photographic data system is the portion based on the ground. The cinetheodolites system is a radar/video combination in which long-range video equipment is slaved to radar equipment tracking airborne test vehicles, usually by means of a beacon onboard the vehicle. The radars are part of the time-space-position instrumentation (TSPI) used to triangulate or define the position of the airborne vehicle, while the video system provides long-range visual data of critical events. The beacon onboard the test vehicle greatly facilitates the tracking ability of the radar. These video data are usually used to

confirm the tracking accuracy of the TSPI radars and serve as a backup to airborne video and photographic data.

14.7 TELEMETRY

14.7.1 INTRODUCTION

A data collection system with telemetry generall consists of transducers, signal conditioning circuits, an airborne multiplexer and a radio frequency transmitter in the aircraft. On the ground, the data collection system consists of an rf receiver, a demultiplexer and a data storage system (usually a tape recorder); in most cases a data (pre) processing system with displays is added for on-line data analysis.

The telemetry part of the system consists of the multiplexer with the associated data modulators, the rf link, the demultiplexer, the data demodulators and the ground recording equipment. In connection with on-line data processing, telemetry has become a powerful means of increasing the capability and efficiency of flight testing.

Telemetry of flight test data has a number of advantages over the use of onboard recording. A telemetry system has less weight and volume, it is less sensitive to extreme environmental conditions than the onboard recorder and it has better quick-look and on-line data processing capabilities. In some types of flight test it would be almost impossible to collect a sufficient quantity of data without telemetry. The use of a second telemetry link from the ground-station to the aircraft (tele-command link) can provide further improvement of the flight test efficiency.

On the other hand there are several drawbacks to the telemetry system. The range is limited by the physical characteristics of wave propagation, and there are problems with the mounting of onboard antennas and with dropouts of data reception due to fading in the radio frequency channel by multipath propagation. The telemetry chain is shown in Figure 39.

The airborne telemetry system consists of the multiplexer, the rf transmitter and the onboard antenna. The radiated signal induces an rf voltage in the receiving antenna. This voltage is amplified and filtered by the receiver in order to eliminate unwanted signals and noise. The demultiplexer decomposes the receiver output signal and recovers the original data.

Finally the data processing equipment converts the received data into the proper form for the user.

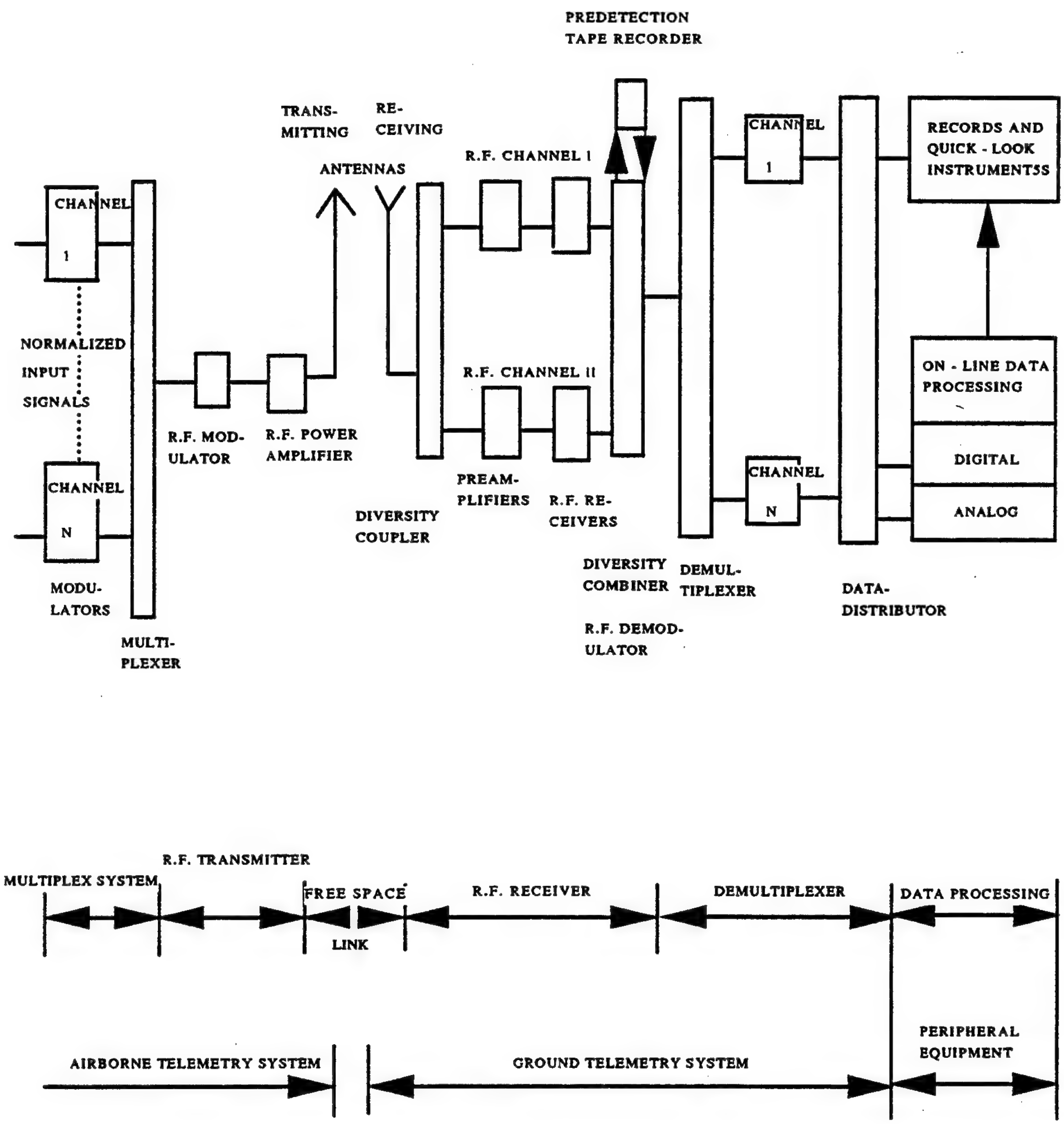


FIGURE 39 BLOCK DIAGRAM OF A TELEMETRY SYSTEM

14.7.2 MODULATION AND MULTIPLEXING

Description of the basic methods:

In general, the purpose of modulation, described earlier, is to match a signal to a specific transmission channel. The purpose of multiplexing is to transmit two or more signals over the same data channel without crosstalk. In practice, data signals are often subjected to both processes.

Modulation and multiplexing used in telemetry systems

In telemetry systems at least two modulation processes are used in cascade. The first is required for each of the multiplexed signals and the second for matching the output signal of the multiplexer to the assigned radio frequency channel. The latter modulation method generally is FM with few exceptions. Telemetry systems are standardized by the Inter Range Instrumentation Group (IRIG).

The FM/FM telemetry system uses frequency division multiplexing (Figure 40). The

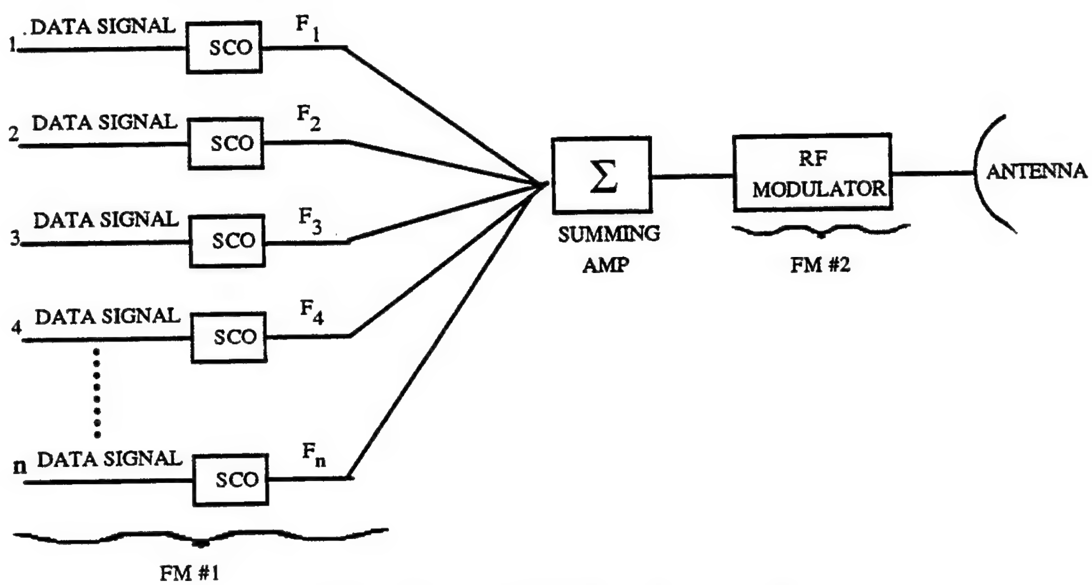


FIGURE 40. FM/FM TELEMETRY

data signals modulate subcarriers with FM (standardized frequency ±7.5% or 15% with optional wideband channels). The maximum number of rf channels is 21 (for the P-band, the number of rf channels is limited to 19). The subcarrier frequencies are located between

400 Hz and 165 kHz. This is true for the proportional bandwidth system, in which the bandwidths of the subcarrier channels increase proportionally to the subcarrier frequency.

The constant bandwidth system provides 21 data channels (15 channels for the P-band frequencies). The subcarrier frequencies are located here between 16 kHz and 176 kHz. The data bandwidth of all channels is equal. Consequently, the signal delay in all channels is equal and the time correlation between the channels is preserved. The hardware available is proven and reliable. This is especially true for airborne subcarrier oscillators and for ground subcarrier discriminators.

In current flight testing, PCM/FM systems are used more and more. Very accurate analog-to-digital converters are now available in integrated circuitry, reducing the cost and complexity of the system. Prior to this integrated circuitry, special decommutators were used in most ground stations. Because computers are being used more and more, decommutation is often along with certain on-line data processing. The bit synchronizer, however, which detects the bit sequence in the noisy background, should preferably not be integrated into the computer.

The telemetry systems mentioned above make use of FM in the rf channel. FM is the only method standardized by IRIG. The other continuous modulation methods such as AM, DSB, and SSB which may also be used for rf modulation, are of little importance.

Mixed systems are often used in practice because only a few flight test signals have a wide bandwidth. Because of past technological difficulties in producing commutators and decommutators with sufficiently high sampling rates, these high frequency data signals were transmitted by frequency multiplexed channels. On the other hand, economic reasons and the moderate number of available frequency-multiplexed channels require the use of time multiplexing for the low frequency data. Due to the recent progress in high speed integrated circuits, wideband PAM and PCM channels are currently available. Therefore straightforward time multiplexing is preferable because of the high flexibility (supercommutation and subcommutation) together with the efficient use of the available bandwidth.

Finally, the inaccuracies introduced by the modulation and multiplexing processes must be considered. Errors originating from hardware imperfections (e.g. zero and gain drift of amplifiers, non-linear distortion) should be distinguished from errors originating from the

peculiarities of the methods used in the system (e.g. sensitivity to noise in the transmission channel). Hardware errors are subject to technological progress, whereas the system method errors must be regarded as inherent to the system.

14.7.3 THE RADIO FREQUENCY LINK

The rf link is the connection between the airborne terminal and the ground station. Because of the following reasons, relatively high transmission frequencies must be used:

a) The electrical length of an antenna must be a significant fraction of the wavelength for reasonable radiation efficiency. The small size required in airborne applications dictates wavelengths smaller than 3 m (frequencies greater than 100 MHz).

b) The high bandwidth required for data transmission is only available at high frequencies. According to IRIG standards three frequency bands are available for telementry. In the range of 216 - 260 MHz (P band) there are 62 channels with 500 kHz bandwidth each. In the range of 1435 - 1540 MHz (L band) there are 100 channels with 1 MHz bandwidth each. In the range of 2200 - 2300 MHz (S band) there are 89 channels with 1 MHz bandwidth each.

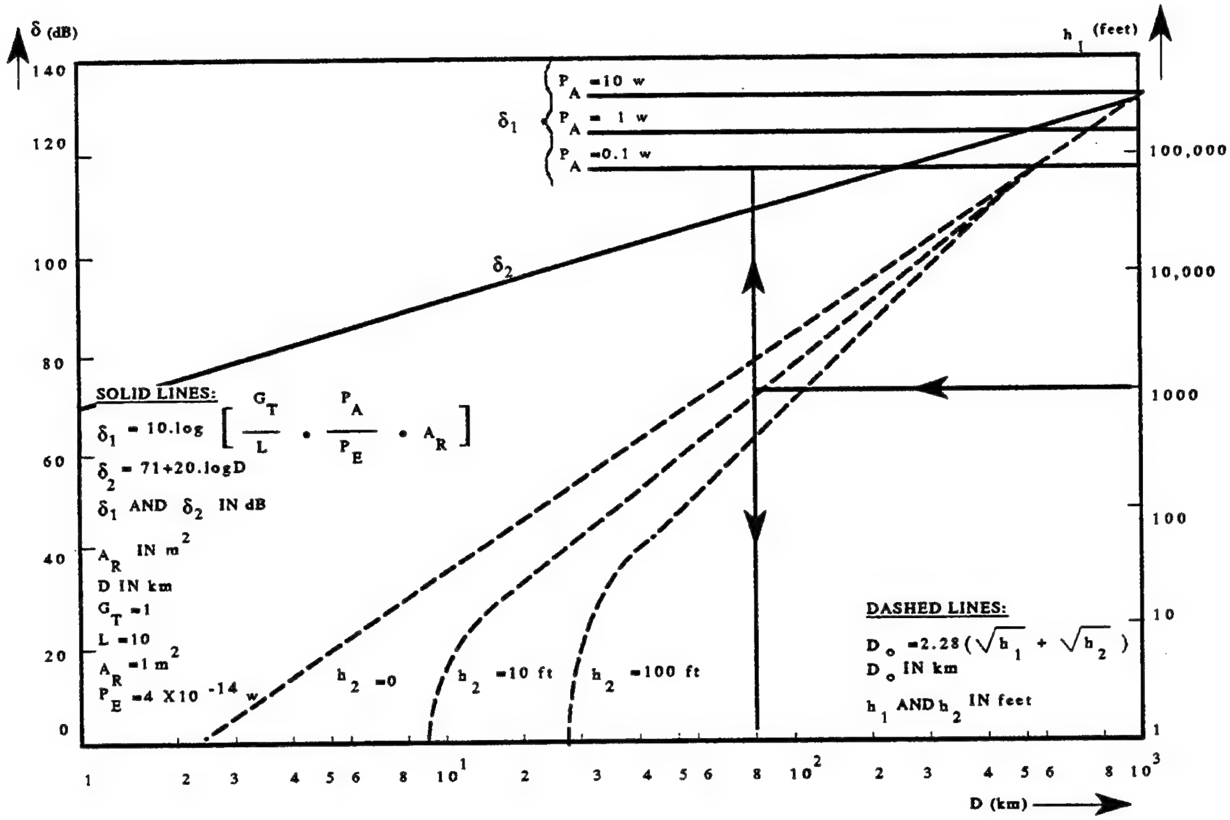


FIGURE 41. SIMPLIFIED PROPAGATION DESIGN CHART

The higher the frequency of an electromagnetic wave, the more its propagation resembles that of light. The usable range between the airborne and the ground terminals is limited by the line of sight if, in a first approximation, the diffraction is neglected. For the L and S band frequencies this can be done with good approximation. Within the line of sight, the formula for wave propagation in free space is a good approximation, provided the heights above ground of the transmitting and the receiving antennas are at least several wavelengths.

The direct line of sight distance D_0 can be calculated by using the formula

$$D_0 = 2.28\ ((h_1)^{1/2} + (h_2)^{1/2})$$

where D_0 = the distance in km

h_1 = the height of the transmitting antenna (in the aircraft) in feet

h_2 = the height of the receiving antenna above the ground in feet.

For three different heights of h_2, the above formula has been displayed in Figure 41 by the dashed lines. Good data reception can be expected for distances, D, between the aircraft and the ground station satisfying the condition

$$D \leq D_0$$

Within this range the required radiated transmitter power can be estimated by using the solid curves in Figure 41. Two auxiliary parameters δ_1 and δ_2 are used. In a logarithmic scale we have

$$\delta_1 = 10.\log \frac{G_T \bullet P_A \bullet A_R}{LP_E}$$

$$\delta_2 = 71 + 20.\log D$$

G_T is the gain of the transmitting antenna. L is the product of losses (cable, mismatching, minima of radiation pattern etc.), P_A and P_E are the transmitted power and the required minimum receiver input power respectively for a given telemetry system. A_R is the effective area of the receiving antenna in square meters and D is the distance between the antennas in km. δ_2, measured in decibels, indicates the attenuation of the transmitted wave as a function of the distance D. In order to obtain good reception, this attenuation must be overcome by δ_1, which contains those parameters which are independent of the distance D.

Thus a supplementary condition to the data reception is

$$\delta_1 \leq \delta_2$$

The plot of δ_1 in Figure 41 is based on the parameters $G_T = 1$;

$L = 10$; $PE = 4.10^{-14}$ W (correct for FM/FM systems); $A_R = 1\ m^2$ and transmitter powers P_A of 0.1 W, 1 W and 10 W. This is roughly equivalent to the practical conditions. G_R is often specified instead of the effective area of the receiving antenna. Then, A_R can be calculated by using the formula

$$A_R = \frac{G_R \bullet \lambda^2}{4 \bullet \pi}$$

where λ is the wavelength.

The use of Figure 41 will be made clear by the following example: For a height of the aircraft of 1000 feet and a height of the receiving antenna of 3.3 m (10 feet), the line of sight is 80 km. With the above-mentioned assumptions we have at this distance a safety margin of 5 db even with a transmitter power of only 0.1 W. This safety margin may be sufficient when using a ground station with diverse reception capabilities. Otherwise, a transmitter power of 1 W would be required in order to overcome fading effects which are not taken into account in Figure 41.

One such fading effect is the so-called fading due to multipath propagation. Sometimes the antenna not only receives the wave coming directly from the transmitter but also a reflected wave (reflected from the ground or from buildings), the phase of which is shifted with respect to the direct wave. Depending on the heights and the distances of the antennas this phase shift may reach 180°. Thus the received signal power may from time to time decrease considerably.

It should be mentioned that the curve δ_2 (D) at the limit of the line of sight is too optimistic. Beyond this limit the wave-attenuation increases even if the transmitter power is substantially increased. On the other hand, the example shows that within the line of sight reliable communication with relatively low transmitter power is possible.

At the receiving end of the telemetry link, double superheterodyne receivers with plug-in techniques are mostly used. Therefore, the receivers can easily be matched to different telemetry systems by choosing the proper tuning modules, intermediate frequency filters, and rf demodulators.

In order to obtain good receiver input sensitivity with low values of P_E the noise figure of the receiver must be kept low. A low-noise preamplifier situated at the antenna is recommended, if it is not possible to locate the antenna near the receiver. The low noise

figure of the preamplifier then determines the noise figure of the receiving system. Reception of L band and S band frequencies can be done with special tuning modules, which are available for standardized telemetry receivers. Alternatively, a frequency down-converter may be mounted at the antenna which converts the L band or S band frequencies to the P band, allowing the existing P band equipment to be used.

Most telemetry receivers can be equipped with an accessory unit for postdetection or predetection diversity combining. Both methods are treated in the next section.

14.7.4 GROUND RECORDING AND DISPLAY

The recovered data signals must be displayed for quick look in the ground station and stored for subsequent data processing. Quick-look display is usually done with pointer instruments as well as with strip-chart recorders and X-Y recorders. Data signals containing frequency components higher than 100 Hz must be recorded by oscillograph recorders. Paper recorders have the advantage of being both a display and a storage device. On the other hand, the limited storage capacity may not meet the high requirements of modern flight tests. Moreover, the information stored in paper recorders can only be converted back into an electrical signal with great difficulty.

In this connection magnetic tape recorders have excellent properties and they are therefore standard equipment in telemetry ground stations. A few years ago postdetection recording was mainly used, in which the frequency-multiplexed signal (FM/FM system) or the time-multiplexed signal (PDM/FM, PAM/FM and PCM/FM system) at the output of the demodulator is recorded on one track of the tape recorder in the direct mode or in the FM mode. The demultiplexing is done during playback. This method allows the recording of a great many data channels. It is also possible to do the demultiplexing on-line, so that the individual data signals are immediately recorded on different tracks of the tape recorder. This method is limited by the maximum number of tracks that can be recorded simultaneously in the ground receiving station. In postdetection recording, the recording method must be matched to the type of multiplexing.

Recently, predetection recording has become more important. The availability of recorders with continuous recording capabilities up to frequencies of 2 MHz allows the direct

recording of the receiver's intermediate frequency (third I.F., maximum 900 kHz) prior to demodulation. The main advantage to this method of recording is that the operation and maintenance of ground stations are simplified. This is the case because the recording method is the same regardless of the type of multiplexing used.

14.7.5 COMPARISON OF IRIG-STANDARDIZED TELEMETRY SYSTEMS

A comparison of the IRIG standardized telemetry systems is made in Table 3 on the basis of 5 different principles. IRIG standards for telemetry systems are well-established, proven and available on the market at reasonable prices. The standards are suitable for almost all measuring problems.

ACCURACY

The accuracy of modem analog systems, when carefully adjusted, approaches ± 1%. The accuracy of the twofold multiplexing in the case of the PAM/FM/FM system can be ± 2%. PCM/FM systems are capable of almost any accuracy required. The only limitation is the accuracy of the transducers and the A/D converters used in the system.

MAXIMUM NUMBER OF DATA CHANNELS

The systems using time-division multiplexing have the highest capacity in number of channels.

MAXIMUM INFORMATION RATE (I.R.)

In Table 3 the I.R. is given in bit/sec. In the case of the analog systems the I.R. is calculated using the significant amplitude resolution and the sampling theorem. The PAM/FM system and the PCM/FM system handle the highest I.R., followed by the FM/FM system. Comparatively, PAM/FM/FM and PDM/FM can handle only very slow information rates.

FLEXIBILITY

Flexibility is very good for systems using time-division multiplexing. Subcommutation and supercommutation can be used to adapt the system to the requirements for the number of channels and frequency response. In the case of PCM/FM it is also possible to use different word lengths for the individual parameters; the individual channels can thereby be adapted to the accuracy of each parameter.

Principles of comparison	I FM - FM proportional bandwidth	II FM - FM constant bandwidth	III PAM - FM - FM	IV PAM - FM	V PDM - FM	VI PCM - FM
Accuracy (careful adjust - ments presupposed)	± 1 % (M = 5)*	± 1 % (M = 5)	± 2 %	± 1 %	± 1 %	Limited by accuracy of transducers or A/D converters only
Maximum number of data channels	19 (VHF band) 21 (UHF band)	15 (VHF band) 21 (UHF band)	128 without sub- commutation. Can be expanded most effectively by subcommutation	See III	90 without sub- commutation. Can be expanded most effectively by subcommuta- tion	Depends on word length. Frame length max. 2048 bit. In practice, all requirements can be met by super- and subcommu- tation
Maximum total information rate (sum of all channels)	VHF band: $65 \times 10^3 \frac{bit}{sec}$ (M=1)* $270 \times 10^3 \frac{bit}{sec}$ (M=1) UHF band: $110 \times 10^3 \frac{bit}{sec}$ (M=5) $460 \times 10^3 \frac{bit}{sec}$ (M=1)	Nearly the same as I	$16700 \frac{bit}{sec}$ (channel I')**	VHF band: $3.6 \times 10^5 \frac{bit}{sec}$ UHF band: $1.8 \times 10^6 \frac{bit}{sec}$	$22 \times 10^3 \frac{bit}{sec}$	VHF band: $2 \times 10^5 \frac{bit}{sec}$ UHF band: $1.2 \times 10^6 \frac{bit}{sec}$
Flexibility (number of chan- nels; channel cut - off freq.)	Moderate (fixed subcarrier fre- quency allocation; only a few varia- tions in channel bandwidth)	See I	Good (low data fre- quencies pre- supposed)	Good	Good (low data fre- quencies pre- supposed)	Excellent supercommutation, variable word length)
Utilization of radio frequency power and radio frequency band - width	Moderate	See I	Poor (can be tolerated as the power re- quirement and the bandwidth is low because of the low information rate)	Good (optimal for moderate accu- racy require- ments)	Good	Good (optimal for high accuracy requirements)

VHF band: P band   UHF band: L and S band   *M = Modulation Index of FM carrier   **Channel with the highest bandwidth of the FM proportional bandwidth subcarrier pattern

TABLE 3. IRIG TELEMETRY SYSTEMS

UTILIZATION OF RADIO FREQUENCY POWER AND BANDWIDTH

It has been found that in the case of high accuracy requirements PCM/FM is the best method for transmitting data with a certain information rate through a band-limited rf channel using minimum rf power. In the case of moderate accuracy requirements PAM/FM requires minimum bandwidth. The widespread FM/FM method is not as good as the PCM/FM method and the PAM/FM method has only poor features in this respect. In the latter case, however, the poor features can be tolerated, since the system carries only low information rates. Normally the PAM/FM method is used in addition to a FM/FM system. The features of the combined system are then determined by the FM/FM method.

14.7.6 ON-LINE DATA PROCESSING

As the data measured in the aircraft are immediately available in the ground station, telemetry makes it possible to observe the measured parameters while the flight is in progress. Until recently this on-line processing and display was mainly used in critical phases of the flights only. In the latest flight tests with military and civil prototypes, telemetry and associated on-line processing is being used in all flight test phases for the majority of the parameters. Although onboard recording is still used as a standby in case telemetry data are lost, there is still a tendency to do most of the analysis from the on-line displays fed by telemetry. Thus, modifications to a flight program can be made during flight. Experience has shown that these real-time displays can reduce the number of flights required in a test program by 30% or more.

The general considerations about data processing are discussed elsewhere. However, a few remarks will be made about on-line computing.

<u>Analog computing methods</u> are very useful means of on-line data processing, especially if the number of channels to be processed is not very large. This method combines the high speed of computation with good adaptability of the hardware to individual problems. The accuracy of the data being processed can be obtained, especially for the quick-look display. An example of a relatively simple application is the computation of indicated airspeed, true airspeed and Mach number from the measured data, total pressure, static pressure and

temperature. About seven operational amplifiers, two multipliers and two square-root function generators are required.

Digital computing has a number of advantages over analog computing. For instance:

- the computation accuracy can be as high as is justified by the accuracy of the input data

- integration can be done without drift (analog integration shows a drift which increases with time) ,

- storage specifications are better (quick access, arbitrarily long duration) ,

- the digital computer can be more readily used for making logical decisions, such as detecting that a signal or a combination of signals has exceeded a certain limit value,

- in a more sophisticated application several measured parameters can be used as an input to a model and the output of the model is compared to other measured parameters (if the difference is too large a special program is initiated),

- the computer can also be used for tasks such as decommutation of PCM signals and for automatic control tasks in the ground station, including automatic control of the receiving antenna, automatic search patterns with high-directivity antennas, and switch-over to autotracking when acquisition is obtained.

A problem with digital on-line computing is that the time required for all computations must be less than the time between two successive data samples. Even very fast computers reach this limit very quickly when handling complex problems.

Hybrid computing may be to some extent a solution to this computation and data sampling rate problem. By combining an analog computer and digital computer, the computing program can be divided into two parts, making optimal use of the advantages of both methods. The interface between the two computers consists essentially of analog-to-digital and digital-to-analog converters. The programming of a hybrid computer is, however, very difficult.